2015-16

Caltech Catalog

California Institute of Technology
Pasadena, California 91125
(626) 395-6811

September 2015

The mission of the California Institute of Technology is to expand human knowledge and benefit society through research integrated with education. We investigate the most challenging, fundamental problems in science and technology in a singularly collegial, interdisciplinary atmosphere, while educating outstanding students to become creative members of society.

While every effort has been made to ensure that this catalog is accurate and up to date, it may include typographical or other errors. The Institute reserves the right to change its policies, rules, regulations, requirements for graduation, course offerings, and any other contents of this catalog at any time.

You can view the *Caltech Catalog* online at http://catalog.caltech.edu/. Please note that the contents of websites that link to online course entries are not part of the official catalog.

Cover: Lance R. Hayashida

CONTENTS

1. General Information

9 Introduction
12 Historical Sketch
19 Buildings and Facilities
30 Undergraduate Research
31 Student Life
37 Student Health
38 Career Development
40 Caltech Alumni Association
41 International Student Programs
41 Auditing Courses
41 Grades and Grading
46 Notices and Agreements
53 Institute Policies

2. Areas of Study and Research

115 Aerospace
119 Applied and Computational Mathematics
120 Applied Mechanics
121 Applied Physics
122 Astrophysics
124 Behavioral and Social Neuroscience
125 Biochemistry and Molecular Biophysics
126 Bioengineering
128 Biology
129 Chemical Engineering
131 Chemistry
133 Civil Engineering
134 Computation and Neural Systems
135 Computer Science
137 Computing and Mathematical Sciences
138 Control and Dynamical Systems
139 Electrical Engineering
144 Energy Science and Technology
145 Environmental Science and Engineering
148 Geological and Planetary Sciences
150 History and Philosophy of Science
150 Humanities
151 Interdisciplinary Studies Program
151 Information Science and Technology
152 Materials Science
153 Mathematics
154 Mechanical Engineering
155 Medical Engineering
156 Microbiology
157 Neurobiology
158 Physics
160 Social Science
161 Systems Biology

3. Information for Undergraduate Students

165 Admission to the Freshman Class
168 Admission to Upper Classes by Transfer
172 Study Abroad
179 ROTC
180 Registration Regulations
184 Scholastic Requirements
188 Undergraduate Expenses
193 Financial Aid
212 Prizes
221 Graduation Requirements, All Options

4. Information for Graduate Students

290 Graduate Policies and Procedures

303 General Requirements for Graduate Degrees
310 Graduate Expenses
312 Financial Assistance
314 Prizes
319 Special Regulations of Graduate Options

5. Courses

407 General Information
408 Aerospace
416 Anthropology
418 Applied and Computational Mathematics
422 Applied Mechanics
424 Applied Physics
429 Art History
433 Astrophysics
438 Biochemistry and Molecular Biophysics
440 Bioengineering
440 Biology
457 Business Economics and Management
460 Chemical Engineering
465 Chemistry
475 Civil Engineering
478 Computation and Neural Systems
482 Computer Science
491 Computing and Mathematical Sciences
493 Control and Dynamical Systems
495 Economics
498 Electrical Engineering
508 Energy Science and Technology
508 Engineering (General)
511 English
521 English as a Second Language
522 Environmental Science and Engineering
527 Film
528 Freshman Seminars
530 Geological and Planetary Sciences
545 History
555 History and Philosophy of Science
564 Humanities
568 Interdisciplinary Studies Program
568 Information Science and Technology
568 Languages
572 Law
573 Materials Science
576 Mathematics
585 Mechanical Engineering
591 Medical Engineering
593 Music
595 Neurobiology
596 Performance and Activities
598 Philosophy
602 Physical Education
608 Physics
617 Political Science
619 Psychology
621 Social Science
626 Writing

6. Trustees, Administration, and Faculty

629 Officers
629 Board of Trustees
633 Administrative Officers
635 Faculty Officers and Committees
639 Staff of Instruction and Research
676 Officers and Faculty

724 Index

ACADEMIC CALENDAR 2015-16

FIRST TERM 2015

September 16–18
International student orientation

September 20–27
New student check-in and orientation for undergraduates

September 21-25
New student check-in and orientation for graduate students

September 24
Undergraduate Academic Standards and Honors Committee—1 p.m.

September 28
Beginning of instruction—8 a.m.

October 16
Last day for adding courses and removing conditions & incompletes

October 28–November 3
Midterm examination period

November 9
Midterm deficiency notices due—9 a.m.

November 11
Faculty meeting—noon to 1 p.m.

November 18
Last day for dropping courses, exercising pass/fail option, and changing sections

November 19–December 4
Registration for second term, 2015–16

November 26–27
Thanksgiving (Institute holiday)

December 4
Last day of classes
Last day to register for second term, 2015–16, without a $50 late fee

December 5-8
Study period

December 9–11*
Final examinations, first term, 2015–16

December 11
End of first term, 2015–16

December 12–January 4
Winter recess

December 16
Instructors' final grade reports due—9 a.m.

December 25-28
Christmas (Institute holiday)

December 29–31
Special release days

SECOND TERM 2016

January 1
New Year's Day (Institute holiday)

January 4
Beginning of instruction—8 a.m.

January 5
Undergraduate Academic Standards and Honors Committee—9 a.m.

January 18
Martin Luther King Day (Institute holiday)

January 22
Last day for adding courses and removing conditions & incompletes

February 3–9
Midterm examination period

February 15
Presidents' Day (Institute holiday)

February 16
Midterm deficiency notices due—9 a.m.

February 22
Faculty meeting—noon to 1 p.m.

February 24
Last day for dropping courses, exercising pass/fail option, and changing sections

February 25–March 9
Registration for third term, 2015–16

March 9
Last day of classes
Last day to register for third term, 2015–16, without a $50 late fee

March 10–13
Study period

March 14–16*
Final examinations, second term, 2015–16

**First due date for final examinations*

March 16
End of second term, 2015–16

March 17–27

Spring recess

March 21
Instructors' final grade reports due—9 a.m.

THIRD TERM 2016

March 28
Beginning of instruction—8 a.m.

March 29
Undergraduate Academic Standards and Honors Committee—9 a.m.

April 15
Last day for adding courses and removing conditions and incompletes

April 27–May 3
Midterm examination period

May 9
Midterm deficiency notices due—9 a.m.
Last day for seniors to remove conditions and incompletes

May 13
Last day for admission to candidacy for the degrees of Master of Science and Engineer, and for scheduling an examination for the degree of Doctor of Philosophy

May 18
Last day for dropping courses, exercising pass/fail option, and changing sections

May 19-June3
Registration for first term, 2016–17, and for summer research

May 27
Last day of classes—seniors and graduate students
Last day for presenting theses for the degrees of Doctor of Philosophy and Engineer

May 28–31
Study period for seniors and graduate students

May 30
Memorial Day (Institute holiday)

June 1–3*
Final examinations for seniors and graduate students, third term, 2015–16

**First due date for final examinations*

June 3
Last day of classes—undergraduates
Last day to register for first term, 2016–17, without a $50 late fee

June 4–7
Study period for undergraduates

June 6
Instructors' final grade reports due for seniors and graduate students—9 a.m.

June 8
Undergraduate Academic Standards and Honors Committee—9 a.m.
Curriculum Committee—10 a.m.
Faculty meeting—2 p.m.-3 p.m.

June 8–10*
Final examinations for undergraduates, third term, 2015–16

June 10
Commencement—10 a.m.
End of third term, 2015–16

June 15
Instructors' final grade reports due for undergraduates—9 a.m.

June 22
Undergraduate Academic Standards and Honors Committee—9 a.m.

July 4
Independence Day (Institute holiday)

September 5
Labor Day (Institute holiday)

FIRST TERM 2016–17

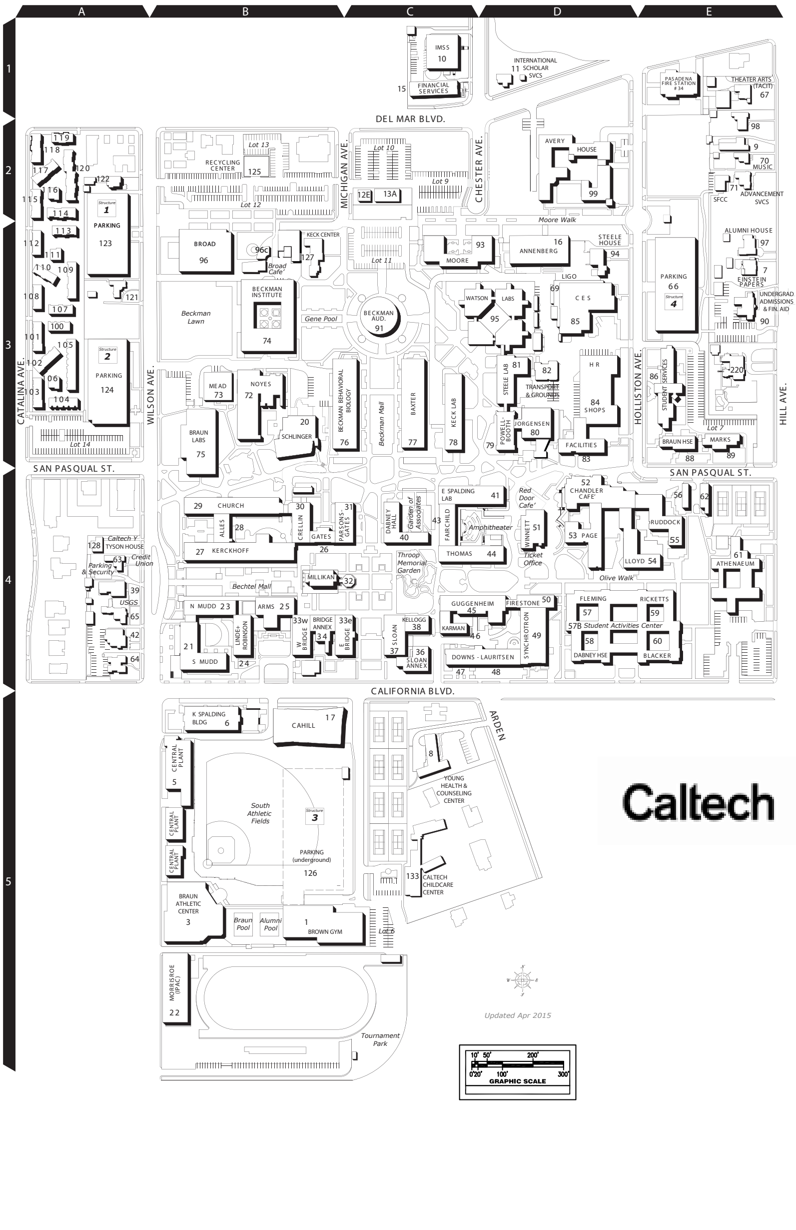
September 14–16
International student orientation

September 18–25
New student check-in and orientation for undergraduates

September 19-23
New student check-in and orientation for graduate students

September 22
Undergraduate Academic Standards and Honors Committee—9 a.m.

September 26
Beginning of instruction—8 a.m.


A
B
C
D
E
1
2
3
4
5
IMSS
10
15
FINANCIAL SERVICES
INTERNATIONAL SCHOLAR SVCS
11
PASADENA FIRE STATION # 34
THEATER ARTS (TACIT)
67
DEL MAR BLVD.
119
118
117
120
122
116
115
114
113
112
111
110
109
108
107
100
101
105
102
06
103
104
121
Structure 1
PARKING
123
Structure 2
PARKING
124
Lot 14
CATALINA AVE.
WILSON AVE.
Lot 13
RECYCLING CENTER
125
Lot 12
MICHIGAN AVE.
Lot 10
Lot 9
12E
13A
CHESTER AVE.
AVERY
HOUSE
99
98
9
70
MUSIC
71
SFCC
ADVANCEMENT SVCS
Moore Walk
BROAD
96
96c
Broad Cafe'
KECK CENTER
127
Lot 11
MOORE
93
16
ANNENBERG
STEELE HOUSE
94
ALUMNI HOUSE
97
PARKING
66
Structure 4
7
EINSTEIN PAPERS
UNDERGRAD ADMISSIONS & FIN. AID
90
LIGO
69
Beckman Lawn
BECKMAN INSTITUTE
74
Gene Pool
BECKMAN AUD.
91
WATSON
LABS
95
C E S
85
MEAD
73
NOYES
72
20
SCHLINGER
BRAUN LABS
75
BECKMAN BEHAVIORAL BIOLOGY
76
Beckman Mall
BAXTER
77
KECK LAB
78
79
POWELL-BOOTH
STEELE LAB
81
82
TRANSPORT & GROUNDS
JORGENSEN
80
H R
84
SHOPS
FACILITIES
83
HOLLISTON AVE.
86
STUDENT SERVICES
220
Lot 7
BRAUN HSE
88
MARKS
89
HILL AVE.
SAN PASQUAL ST.
SAN PASQUAL ST.
128
Caltech Y
TYSON HOUSE
63
Credit Union
Parking & Security
39
USGS
65
42
64
29
CHURCH
30
31
ALLES
28
CRELLIN
GATES
PARSONS-GATES
27
KERCKHOFF
26
DABNEY HALL
40
Garden of Associates
43
E SPALDING LAB
41
FAIRCHILD
Amphitheater
THOMAS
44
Red Door Cafe'
WINNETT
51
Ticket Office
52
CHANDLER CAFE'
53
PAGE
RUDDOCK
55
56
62
LLOYD
54
61
ATHENAEUM
Olive Walk
Throop Memorial Garden
MILLIKAN
32
Bechtel Mall
N MUDD
23
ARMS
25
21
S MUDD
24
LINDE+ ROBINSON
33w
W BRIDGE
BRIDGE ANNEX
34
33e
E BRIDGE
SLOAN
37
KELLOGG
38
36
SLOAN ANNEX
GUGGENHEIM
45
KARMAN
46
FIRESTONE
50
SYNCHROTRON
49
DOWNS - LAURITSEN
47
48
FLEMING
57
RICKETTS
59
57B
Student Activities Center
58
DABNEY HSE
60
BLACKER
CALIFORNIA BLVD.
K SPALDING BLDG
6
CAHILL
17
ARDEN
8
YOUNG HEALTH & COUNSELING CENTER
CENTRAL PLANT
5
CENTRAL PLANT
CENTRAL PLANT
South Athletic Fields
Structure 3
PARKING (underground)
126
133
CALTECH CHILDCARE CENTER
BRAUN ATHLETIC CENTER
3
Braun Pool
Alumni Pool
1
BROWN GYM
Lot 6
MORRISROE (IPAC)
22
Tournament Park
Updated Apr 2015
Caltech
10'
50'
200'
0'20'
100'
300'
GRAPHIC SCALE

Campus Map

Caltech Campus Building Directory

Buildings by Name	Bldg No	Map Grid
263 S Chester (International Scholar Services)	11	D1
275 S Hill (Theater Arts (TACIT))	67	E1
287 S Hill (Rickenbaugh House)	98	E1
295 S Hill	9	E2
305 S Hill (Music House)	70	E2
315 S Hill (Advancement Svcs (front) SFCC (rear))	71	E2
315 S Wilson	122	A2
320 S Michigan Ave	12E	C2
330 S Michigan Ave (Audio Visual Annex)	13A	C2
345 S Hill (Alumni House)	97	E2
355 S Holliston (Steele House)	94	D3
363 S Hill (Einstein Papers House)	7	E3
375 S Wilson (Prufrock House)	121	A3
383 S Hill (Undergrad Admissions & Financial Aid)	90	E3
415 S Hill Ave	220	E3
505 S Wilson (Tyson House/Caltech Y)	128	A4
515 S Wilson (Credit Union/Parking & Security)	63	A4
525 S Wilson (U.S. Geological Survey)	39	A4
535 S Wilson (Fitzhugh House/USGS)	65	A4
551 S Wilson (Investment Office)	42	A4
565 S Wilson (Audit Svcs & Inst Compliance)	64	A4
1320 San Pasqual St	56	E4
1350 San Pasqual St	62	E4
Alles Laboratory	28	B4
Annenberg Center for Info Sci and Tech (IST)	16	D3
Arms Laboratory	25	B4
Athenaeum	61	E4
Avery House	99	D2
Baxter Hall	77	C3
Beckman Auditorium	91	C3
Beckman Behavioral Biology Labs (BBB)	76	B3-C3
Beckman Institute	74	B3
Blacker House	60	E4
Braun Athletic Center	3	B5
Braun House	88	E3
Braun Laboratories	75	B3
Bridge Annex	34	B4
Bridge Laboratory - East	33E	B4
Bridge Laboratory - West	33W	B4
Broad Café	96C	B3
Broad Center for the Biological Sciences	96	B3
Brown Gymnasium	1	B5
Cahill Center for Astroscience and Astrophysics	17	B5
Caltech Childcare Center (New)	133	C5
Catalina Graduate Housing	100-120	A2-A3
Central Engineering Services (CES)	85	D3
Central Plant (incl. Cogen & Cooling Towers)	5	B5
Chandler Dining Hall (Chandler Café)	52	D4
Church Laboratory	29	B4
Crellin Laboratory	30	B4
Dabney Hall	40	D4
Dabney House	58	D4
Downs Laboratory (Downs-Lauritsen Labs)	47	C4
Facilities/Facilities Management	83	D3
Financial Services	15	C1
Firestone Laboratory	50	D4
Fleming House	57	D4
Gates Annex	26	B4
Guggenheim Laboratory	45	C4
Human Resources/Facilities Management Shops	84	D3
Information Management Systems & Svcs (IMSS)	10	C1
Jorgensen Laboratory	80	D3
Karman Laboratory	46	C4
Keck Center	127	B3
Keck Laboratories	78	C3
Kellogg Radiation Laboratory	38	C4
Kerckhoff Annex	27A	B4
Kerckhoff Laboratories	27	B4
Lauritsen Laboratory (Downs-Lauritsen Labs)	48	D4
LIGO	69	D3
Linde+Robinson Laboratory	24	B4
Lloyd House	54	D4-E4
Marks House	89	E3
Mead Laboratory	73	B3
Millikan Library	32	B4
Moore Laboratory	93	C3
Morrisroe Astroscience Laboratory (IPAC)	22	B5
Mudd Laboratories - North	23	B4
Mudd Laboratories - South	21	B4
Noyes Laboratory	72	B3
Page House	53	D4
Parking Structure 1 (North Wilson Avenue)	123	A3
Parking Structure 2 (South Wilson Avenue)	124	A3
Parking Structure 3 (California Avenue)	126	B5
Parking Structure 4 (Holliston Avenue)	66	E3
Parsons-Gates Hall of Administration	31	B4
Powell-Booth Laboratory	79	D3
Recycling Center	125	B2
Ricketts House	59	E4
Ruddock House	55	E4
Satellite Utility Plant	66B	E3
Schlinger Lab for Chemistry and Chem Engr	20	B3
Sherman Fairchild Library	43	C4
Sloan Annex	36	C4
Sloan Laboratory	37	C4
South Undergrad Housing Complex Basement	57B	D4
Spalding Lab, Eudora (Eudora Spalding Lab)	41	C4
Spalding, Keith (Keith Spalding Building)	6	B5
Steele Laboratory	81	D3
Student Activities Center	57B	D4
Student Services, Center for (CSS)	86	E3
Synchrotron Laboratory	49	D4
Thomas Laboratory	44	C4
Transportation & Grounds Operations	82	D3
Undergraduate Admissions & Financial Aid	90	E3
Watson Laboratories	95	C3-D3
Winnett Center (Café/Bookstore/Ticket Offc)	51	D4
Young Health and Counseling Center	8	C5

General Information

INTRODUCTION

People who follow the news in science and engineering are often astonished the first time they see Caltech. Unadorned signs mark the borders of a campus that is just half a mile across. Inside, gardens, fountains, and café patios fill sunny spaces between historic buildings. The small, park-like campus comes as a surprise, given Caltech's record of world-changing discoveries and inventions and the luminaries educated here.

Behind the gracious old façades—and several striking contemporary ones—are some of the world's most advanced laboratories. In addition, faculty and students develop and use facilities around the world and in space. They founded NASA's Jet Propulsion Laboratory (JPL), which is managed by Caltech and is an integral partner in research. JPL enables the nation to explore space for the benefit of humankind by developing robotic space missions. Caltech also manages major collaborations such as a Department of Energy research hub to work toward artificial photosynthesis and the Laser Interferometer Gravitational-Wave Observatory, or LIGO, which involves some 500 scientists worldwide in the effort to directly detect ripples in space-time. Faculty and students design instruments and experiments for the world's particle accelerators, seismic networks, pollution-research aircraft, deep-ocean submersibles, and ground- and space-based observatories studying Earth, the planets, and the cosmos.

Caltech students and faculty pioneered the fields of molecular biology, geochemistry, aerospace, earthquake engineering, and astrophysics, to name just a few. They developed the principles of jet flight, key tenets of seismology (including the Richter scale), methodologies for integrated circuit design, empirical and laboratory approaches for economics and political science, and technology to view and study chemical reactions at the atomic level as they occur. They discovered fundamental building blocks of matter, the nature of chemical bonds, the specializations of the left and right brain hemispheres, the role played by chromosomes in heredity, the age of Earth, the origin of elements by reactions in stars, and the geometry of the universe.

The effect of Caltech's dedication to fundamental research combined with enabling technologies is evident in the more than 2,600 U.S. patents Caltech has obtained since 1980, outstripping other universities on a per capita basis. Forty to fifty Caltech inventions are commercially licensed each year. Since 1995, faculty and students have created more than 180 start-up companies. And these numbers—and the contributions to science and society mentioned above—do not touch on the accomplishments of alumni who have left Caltech for diverse careers around the world.

Caltech's history of achievement stems from the caliber of people who choose to come here and from their ready access to other superb scholars and to cutting-edge facilities. When undergraduates arrive, they have the opportunity—sometimes for the first time in their lives—to discuss with passion exciting, challenging problems in science, math, and engineering with people who can respond in kind. Many work side by side with faculty in the labs before their first year is out. Together, faculty and students stretch themselves intellectually, moving ahead fast and sometimes leaving whole new fields in their wakes.

The following pages offer an overview of Caltech's aims and programs and a brief history of how it evolved into one of the world's major research institutions.

Mission, Educational Objectives, and Structure

The mission of the California Institute of Technology (Caltech) is to expand human knowledge and benefit society through research integrated with education. We investigate the most challenging, fundamental problems in science and technology in a singularly collegial, interdisciplinary atmosphere, while educating outstanding students to become creative members of society.

Caltech provides an outstanding education that prepares students to become world leaders in science, engineering, academia, business, and public service. The Institute aims for these educational outcomes:

- Graduates can analyze, synthesize, and communicate ideas.
- Graduates demonstrate integrity, personal and professional responsibility, and respect for others.
- Bachelor of Science graduates can identify, analyze, and solve challenging problems within and across science and engineering disciplines.
- Bachelor of Science graduates can apply their analytic skills to other areas of knowledge and understand issues important in our society.
- Master of Science graduates can apply advanced knowledge in a specialized area in preparation for their professional careers.
- Doctor of Philosophy graduates can independently identify, analyze, and solve fundamental research problems with breadth and depth.

Caltech is an independent, privately supported university. It has six academic divisions: Biology and Biological Engineering; Chemistry and Chemical Engineering, Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics and Astronomy.

Undergraduate Program

Undergraduates earn Bachelor of Science (B.S.) degrees, with options (majors) available in applied and computational mathematics; applied physics; astrophysics; bioengineering; biology; business economics and management; chemical engineering; chemistry; computer science; economics; electrical engineering; engineering and applied science; English; geobiology; geochemistry; geology; geophysics; history; history and philosophy of science; interdisciplinary studies; mathematics; mechanical engineering; philosophy; physics; planetary science; and political science.

A Caltech education includes not just the depth of an option, but also breadth in the basic sciences, humanities, and social sciences. Required courses in biology, chemistry, humanities, mathematics, physics, and the social sciences expose students to diverse intellectual pursuits and help prepare students for the interdisciplinary nature of contemporary research in science and technology. Caltech has offered more than 275 humanities and social science courses, and most students take more than the number required. Students also take three or more terms of physical education, and 80 percent participate in an organized intramural/recreational competition each year—one of the highest participation rates in the country. Thirty percent participate in intercollegiate athletics.

Most students select an option near the end of their first year, begin to specialize during their second year, and concentrate on their chosen field in their third and fourth years. Some students participate in overseas programs at other major research universities in their junior or senior years. Throughout their education, students have opportunities to do hands-on research, and they often design their own faculty-mentored summer research projects (see SURF details on page 30). Premedical students may gain clinical experience via joint programs with four renowned hospitals.

Caltech offers students many academic options and opportunities for personal growth, and also offers unequaled training in rigorous thinking, scientific methodology, and creative problem solving. That training, the company of like minds, and Caltech's collaborative ethic prepare students to take leadership roles in research, academia, and industry, and to find lifelong satisfaction in their work and friendships.

To learn more, see www.admissions.caltech.edu.

Graduate Program

Caltech offers graduate students rigorous research training and a strong, flexible curriculum of course work. Graduate students make up more than half of the student body.

Graduate options include aeronautics; applied and computational mathematics; applied mechanics; applied physics; astrophysics; behavioral and social neuroscience; biochemistry and molecular biophysics; bioengineering; biology; chemical engineering; chemistry; civil engineering; computing and mathematical sciences; computation and neural systems; computer science; control and dynamical systems; electrical engineering; environmental science and engineering; geobiology; geochemistry; geology; geophysics; materials science; mathematics; mechanical engineering; medical engineering; neurobiology; physics; planetary science; social sciences; and space engineering.

Jointly engaged with faculty to complete innovative research at the forefront of each of these fields, graduate students sustain Caltech's atmosphere of intellectual curiosity and creative activity.

Caltech admits students working toward the degree of Master of Science (M.S.), the degree of Engineer in certain fields, and the degree of Doctor of Philosophy (Ph.D.).

To learn more, see www.gradoffice.caltech.edu.

Postdoctoral and Senior Postdoctoral Scholars*

More than 500 early-career scientists and engineers conduct research at Caltech as postdoctoral scholars. In addition, the Jet Propulsion Laboratory (administered by Caltech) hosts postdoctoral scholars whose studies cover many aspects of earth, planetary, astrophysical, and technology research. All scholars work under the supervision of professorial faculty members or JPL researchers.

* Information for newly appointed postdoctoral scholars is available through Human Resources (https://hr.caltech.edu/work/postdocs) and the Caltech Postdoctoral Association (www.cpa.caltech.edu). Upon arrival, scholars should call a postdoctoral-scholar specialist in HR (626-395-6586) to make appointments to activate their positions. In virtually all circumstances, postdoctoral scholars must have earned a doctorate from a duly accredited institution.

HISTORICAL SKETCH

The California Institute of Technology developed from a local manual-arts school established in Pasadena in 1891 by the Honorable Amos G. Throop. Initially founded as Throop University, it was later renamed Throop Polytechnic Institute. Known as the California Institute of Technology since 1920, it has long enjoyed the support of the citizens of Pasadena. As early as 1908, the Board of Trustees had as members Dr. Norman Bridge, Arthur H. Fleming, Henry M. Robinson, J. A. Culbertson, C. W. Gates, and Dr. George Ellery Hale. These men dedicated their time, their minds, and their fortunes to transforming a modest vocational school into a university capable of attracting to its faculty some of the world's most eminent scholars and scientists.

George Ellery Hale, astronomer and first director of the Mount Wilson Observatory, foresaw the development in Pasadena of a distinguished institution of engineering and scientific research. Hale knew that modern, well-equipped laboratories were essential to such an institution's development, but he stressed to his fellow trustees that the focus was to be on men, not machines. "We must not forget," he wrote in 1907, "that the greatest engineer is not the man who is trained merely to understand machines and apply formulas, but is the man who, while knowing these things, has not failed to develop his breadth of view and the highest qualities of his imagination. No creative work, whether in engineering or in art, in literature or in science, has been the work of a man devoid of the imaginative faculty."

The realization of these aims meant specializing, so the trustees decided in 1907 to discontinue the elementary school, the business school, the teacher-training program, and the high school, leaving only a college of science and technology that conferred Bachelor of Science degrees in electrical, mechanical, and civil engineering.

In 1910 Throop Polytechnic Institute moved from its crowded quarters in the center of Pasadena to a new campus of 22 acres on the southeastern edge of town, the gift of Arthur H. Fleming and his daughter Marjorie. The president, Dr. James A. B. Scherer, and his faculty of 16 members opened the doors to 31 students that September. When, on March 21, 1911, Theodore Roosevelt delivered an address at Throop Institute, he declared, “I want to see institutions like Throop turn out perhaps ninety-nine of every hundred students as men who are to do given pieces of industrial work better than any one else can do them; I want to see those men do the kind of work that is now being done on the Panama Canal and on the great irrigation projects in the interior of this country—and the one-hundredth man I want to see with the kind of cultural scientific training that will make him and his fellows the matrix out of which you can occasionally develop a man like your great astronomer, George Ellery Hale.”

It would have surprised Roosevelt to know that within a decade the little Institute, known from 1913 as Throop College of Technology, would have again set its sights higher, leaving to others the training of more efficient technicians and concentrating its own efforts on Roosevelt’s “hundredth man.” On November 29, 1921, the trustees declared it to be the express policy of the Institute to pursue scientific research of the greatest importance and at the same time “to continue to conduct thorough courses in engineering and pure science, basing the work of these courses on exceptionally strong instruction in the fundamental sciences of mathematics, physics, and chemistry; broadening and enriching the curriculum by a liberal amount of instruction in such subjects as English, history, and economics; and vitalizing all the work of the Institute by the infusion in generous measure of the spirit of research.”

Three men were responsible for the change in the Institute. George Ellery Hale still held to his dream. Arthur Amos Noyes, professor of physical chemistry and former acting president of the Massachusetts Institute of Technology, served part of each year from 1913 to 1919 as professor of general chemistry and as research associate; then, in 1919, he resigned from MIT to devote himself full-time to Throop as director of chemical research. In a similar way Robert Andrews Millikan began, in 1916–17, to spend a few months a year at Throop as director of physical research. Shortly after the school was renamed in 1920, Scherer resigned as president. In 1921, when Dr. Norman Bridge agreed to provide a research laboratory in physics, Millikan resigned from the University of Chicago and became administrative head of the Institute as well as director of the Norman Bridge Laboratory.

The great period of the Institute’s life began, then, under the guidance of three men of vision—Hale, Noyes, and Millikan. They were distinguished research scientists who soon attracted graduate students. In 1920 the enrollment was nine graduate students and 359 undergraduates with a faculty of 60; a decade later there were 138 graduate students, 510 undergraduates, and a faculty of 180. At the present time there are over 900 undergraduates, 1,200 graduate students, and some 300 professorial faculty and 700 postdoctoral scholars.

The Institute also attracted financial support from individuals, corporations, and foundations. In January 1920 the endowment had reached half a million dollars. In February of that year, it was announced that $200,000 had been secured for research in chemistry and a like amount for research in physics. Other gifts followed from trustees and friends who could now feel pride in the Institute as well as hope for its future. The Southern California Edison Company provided a high-voltage laboratory with the million-volt Sorensen transformer. Philanthropic foundations bearing the names of Carnegie, Rockefeller, and Guggenheim came forth with needed help when new departments or projects were organized.

In 1923 Millikan received the Nobel Prize in Physics. He had attracted to the Institute such men as Charles Galton Darwin, Paul Epstein, and Richard C. Tolman. The first Ph.D. was awarded in 1920. In 1924, the degree was awarded to nine candidates.

It was inevitable that the Institute would expand upon its fields; it could not continue to be merely a research and instructional center in physics, chemistry, and engineering. But the trustees pursued a cautious and conservative policy, not undertaking to add new departments except when the work done in them would be at the same high level as that in physics and chemistry. In 1925 a gift of $25,000 from the Carnegie Corporation of New York made possible the opening of a department of instruction and research in geology. A seismological laboratory was constructed, and Professors John P. Buwalda and Chester Stock came from the University of California to lead the work in the new division.

That same year, William Bennett Munro, chairman of the division of history, government, and economics at Harvard, joined the Institute faculty. Offerings in economics, history, and literature were added to the core of undergraduate instruction.

In 1928 Caltech began its program of research and instruction in biology. Thomas Hunt Morgan became the first chairman of the new Division of Biology and a member of Caltech's Executive Council. Under Morgan's direction, the work in biology developed rapidly, especially in genetics and biochemistry. Morgan received the Nobel Prize in 1933.

The Guggenheim Graduate School of Aeronautics was founded at Caltech in the summer of 1926, and a laboratory was built in 1929, but courses in theoretical aerodynamics had been given at the Institute for many years by professors Harry Bateman and Paul Epstein. As early as 1917, the Throop Institute had constructed a wind tunnel in which, the catalog boasted, constant velocities of 4 to 40 miles an hour could be maintained, "the controls being very sensitive." The new program, under the leadership of Theodore von Kármán, included graduate study and research at the level of the other scientific work at the Institute, and what is now known as GALCIT (Graduate Aerospace Laboratories at the California Institute of Technology) was soon a world-famous research center in aeronautics.

In 1928, George Ellery Hale and his associates at the Mount Wilson

Observatory developed a proposal for a 200-inch telescope and attracted the interest of the General Education Board of the Rockefeller Foundation in providing $6 million for its construction. The board proposed that the gift be made, and Caltech agreed to be responsible for the construction and operation. The huge instrument was erected on Palomar Mountain and began operation in 1948. Teaching and research in astronomy and astrophysics thus became a part of the Caltech program.

From the summer of 1940 until 1945, Caltech devoted an increasingly large part of its personnel and facilities to furthering the national defense and war effort. Caltech's work during this period fell mainly into two categories: special instructional programs and weapons research. The research and development work was carried out, for the most part, under nonprofit contracts with the Office of Scientific Research and Development. Rockets, jet propulsion, and antisubmarine warfare were the chief fields of endeavor. The Jet Propulsion Laboratory in the upper Arroyo Seco continues, under Institute management, to conduct a large-scale program of research for the National Aeronautics and Space Administration and other agencies in the science and technology of robotic space exploration.

In the 1950s, in response to the growing technological component, and complexity, of societal problems, the Institute began to expand the fields in which it had substantial expertise. In the late 1960s and early 1970s, the Institute added to its faculty several economists and political scientists who initiated theoretical and applied studies of interdisciplinary issues. A graduate program in social sciences was added in 1972. Caltech students could now engage their talents in the development of the basic scientific aspects of economics and political science, and begin to use the principles from these sciences together with those from the physical sciences to formulate and address public policies.

In 1945 Robert A. Millikan retired as chairman of the Executive Council, but he served as vice chairman of the Board of Trustees until his death in 1953. Dr. Lee A. DuBridge became president of Caltech on September 1, 1946. Formerly chairman of the physics department and dean of the faculty at the University of Rochester, he came to the Institute after working for five years as wartime director of the MIT Radiation Laboratory—and remained for 22 years.

DuBridge was also committed to the concept of a small, select institution offering excellence in education. Facts and figures are only part of the story, but the statistical record of change during the DuBridge administration indicates how he held to that concept. The 30-acre campus of 1946 grew to 80 acres; the $17 million endowment grew to more than $100 million; the faculty of 260 became 550; the number of campus buildings increased from 20 to 64; and the budget went from something less than $8 million to $30 million. But enrollment remained relatively constant. In 1946 the total number of students, graduate and undergraduate, was 1,391. In 1968, the year DuBridge left, it was 1,492.

Dr. Harold Brown came to Caltech as president in 1969. A physicist who had received his Ph.D. from Columbia in 1949, he had succeeded Dr. Edward Teller as director of the University of California's Lawrence Radiation Laboratory in Livermore in 1960. President Lyndon Johnson named Brown Secretary of the Air Force in 1965, and he came to the Institute from that office. Six new campus buildings were dedicated under Brown's administration, and a major development campaign for $130 million was under way when he resigned in 1977 to become Secretary of Defense under President Carter.

With Brown's departure, Robert F. Christy became Acting President, and served in that capacity from 1977 to 1978, while continuing to serve as the Institute's Vice President and Provost.

Dr. Marvin L. Goldberger was appointed president in 1978. He had received his B.S. at the Carnegie Institute of Technology (now Carnegie Mellon University) and his Ph.D. at the University of Chicago. He came to Caltech from Princeton University, where he was the Joseph Henry Professor of Physics. Among the major accomplishments of the Goldberger administration were the addition of three new laboratories, the acquisition of a $70 million grant for construction of the W. M. Keck Observatory to house the world's most powerful optical telescope, and a $50 million pledge for the establishment of the Beckman Institute. Goldberger resigned in 1987 to become director of the Institute for Advanced Study in Princeton, New Jersey.

In the fall of 1987, Dr. Thomas E. Everhart became president, coming to Caltech from his position as chancellor at the University of Illinois at Urbana-Champaign. Everhart graduated magna cum laude with an A.B. in physics from Harvard, received his M.Sc. in applied physics from UCLA, and earned a Ph.D. in engineering from Cambridge University. He had gained international recognition for his work in the development of electron microscopy, and he had also done research on electron beams as applied to the analysis and fabrication of semiconductors. Everhart retired as president in October 1997, but he retains a faculty position as emeritus professor of electrical engineering and applied physics. During his tenure in office, he oversaw construction of the Keck Observatory in Hawaii, the Moore Laboratory of Engineering, Avery House, the Braun Athletic Center, the Sherman Fairchild Library, and the Beckman Institute, and he directed the successful completion of a $350 million campaign for Caltech.

In October 1997, Dr. David Baltimore assumed the presidency of the Institute. One of the world's leading biologists, he received the 1975 Nobel Prize for his work in virology. Previously the Ivan R. Cottrell Professor of Molecular Biology and Immunology at MIT and founding director of its Whitehead Institute for Bio-medical Research, Baltimore had also served as president of Rockefeller University, where he earned his doctorate in 1964.

He played a pivotal role in creating a consensus on national science policy regarding recombinant DNA research, served as chairman of the National Institutes of Health (NIH) AIDS Vaccine Research Committee, and in 1999 was awarded the National Medal of Science by President Clinton.

In late 2006, Baltimore stepped down from the Caltech presidency, returning to his research as the Institute's Millikan Professor of Biology. During his administration, he successfully completed a $100 million campaign to support biological research, resulting in the construction of the Broad Center for the Biological Sciences. He also launched a $1.4 billion comprehensive campaign. By the time he returned to his lab, the campaign was near completion: three new laboratories had been funded, and the Thirty-Meter Telescope had passed its conceptual design review phase.

Dr. Jean-Lou Chameau became Caltech's eighth president in September 2006. The former provost and vice president for academic affairs at the Georgia Institute of Technology, he was also a Georgia Research Alliance Eminent Scholar and the Hightower Professor, and he earlier served as dean of the Georgia Tech College of Engineering. Chameau, whose research interests have included sustainable technology, environmental geotechnology, soil dynamics, earthquake engineering, and liquefaction of soils, received his undergraduate education in France and his Ph.D. in civil engineering from Stanford University.

During his tenure at the Institute, Chameau oversaw the conclusion of the largest fund-raising campaign in Caltech's history, and the construction of the Cahill Center for Astronomy and Astrophysics, the Annenberg Center for Information Science and Technology, the Schlinger Laboratory for Chemistry and Chemical Engineering, the Linde + Robinson Laboratory for Global Environmental Science, and the Earle M. Jorgensen Laboratory. Known for his commitment to cross-disciplinary collaboration, Chameau placed strong emphasis on improving the educational experience at Caltech, increasing diversity, and fostering research, entrepreneurial, and international opportunities for faculty and students. Chameau left Caltech in June 2013 to become president of the King Abdullah University of Science and Technology in Thuwal, Saudi Arabia.

Following Dr. Chameau's departure, Edward M. Stolper assumed the position of interim president from 2013-14, while continuing to serve as provost of the Institute.

On July 1, 2014, Dr. Thomas F. Rosenbaum took office as Caltech's ninth president. Dr. Rosenbaum was formerly the John T. Wilson Distinguished Service Professor of Physics at the University of Chicago, where he served as the University's provost for seven years. As provost, he had responsibility for a broad range of institutions and intellectual endeavors across the sciences, arts, and professional schools. He was deeply engaged with Argonne National Laboratory as the University's vice president for research and for Argonne National Laboratory from 2002 to 2006 and as a member of Argonne's Board of Governors.

Dr. Rosenbaum is an expert on the quantum mechanical nature of materials—the physics of electronic, magnetic, and optical materials at the atomic level—that are best observed at temperatures near absolute zero. His honors include an Alfred P. Sloan Research Fellowship, a Presidential Young Investigator Award, and the William McMillan Award for "outstanding contributions to condensed matter physics."

Dr. Rosenbaum is an elected fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. He received his bachelor's degree in physics with honors from Harvard University and both an M.A. and a Ph.D. in physics from Princeton University.

As Caltech has developed in effectiveness and prestige, it has attracted a steady flow of gifts for buildings, endowment, and current operations, in particular during the last campaign. In addition, substantial grants and contracts from the federal government and private sources support many research activities.

Caltech has more than 23,000 living alumni all over the world, many of them eminent in their fields of engineering, science, law, medicine, academe, and entrepreneurship.

Caltech Nobel Laureates

Robert A. Millikan	Physics	1923
Thomas Hunt Morgan	Physiology or Medicine	1933
Carl D. Anderson, B.S. '27, Ph.D. '30	Physics	1936
Edwin M. McMillan, B.S. '28, M.S. '29	Chemistry	1951
Linus Pauling, Ph.D. '25	Chemistry	1954
	Peace Prize	1962
William Shockley, B.S. '32	Physics	1956
George W. Beadle	Physiology or Medicine	1958
Donald A. Glaser, Ph.D. '50	Physics	1960
Rudolf Mössbauer	Physics	1961
Charles H. Townes, Ph.D. '39	Physics	1964
Richard Feynman	Physics	1965
Murray Gell-Mann	Physics	1969
Max Delbrück	Physiology or Medicine	1969
* David Baltimore	Physiology or Medicine	1975
Renato Dulbecco	Physiology or Medicine	1975
Leo James Rainwater, B.S. '39	Physics	1975
Howard M. Temin, Ph.D. '60	Physiology or Medicine	1975
William N. Lipscomb, Ph.D. '46	Chemistry	1976
Robert W. Wilson, Ph.D. '62	Physics	1978
Roger W. Sperry	Physiology or Medicine	1981
Kenneth G. Wilson, Ph.D. '61	Physics	1982
William A. Fowler, Ph.D. '36	Physics	1983
* Rudolph A. Marcus	Chemistry	1992
Edward B. Lewis, Ph.D. '42	Physiology or Medicine	1995

Douglas D. Osheroff, B.S. ’67	Physics	1996
Robert C. Merton, M.S. ’67	Economics	1997
* Ahmed H. Zewail	Chemistry	1999
Leland H. Hartwell, B.S. ’61	Physiology or Medicine	2001
Vernon L. Smith, B.S. ’49	Economics	2002
* Hugh David Politzer	Physics	2004
* Robert H. Grubbs	Chemistry	2005
Martin Karplus, Ph.D. ’54	Chemistry	2013
Eric Betzig, BS ’83	Chemistry	2014

* *In residence*

Caltech Crafoord Laureates

* Gerald J. Wasserburg	Geosciences	1986
Allen R. Sandage, Ph.D. ’53	Astronomy	1991
Seymour Benzer	Biosciences	1993
* Don L. Anderson, M.S. ’58, Ph.D. ’62	Geosciences	1998
James E. Gunn, Ph.D. ’66	Astronomy	2005
Walter H. Munk, B.S. ’39, M.S. ’40	Geosciences	2010
Andrea M. Ghez, MS ’89, Ph.D. ’93	Astronomy	2012

* *In residence*

BUILDINGS AND FACILITIES

On-Campus Buildings

Gates and Crellin Laboratories of Chemistry: first unit, 1917; second unit, 1927; third unit, 1937. The first two units were the gifts of Messrs. C. W. Gates and P. G. Gates of Pasadena; the third unit was the gift of Mr. and Mrs. E. W. Crellin of Pasadena. Gates (first unit), which was retired after suffering extensive damage in the 1971 earthquake, was rebuilt in 1983 as the Parsons-Gates Hall of Administration.

The Arnold and Mabel Beckman Laboratory of Chemical Synthesis, 1986, occupying portions of Crellin Laboratory (as well as portions of Church Laboratory for Chemical Biology), was built with funds provided by the Arnold and Mabel Beckman Foundation.

Norman Bridge Laboratory of Physics: first unit, 1922; second unit, 1924; third unit, 1925. The gift of Dr. Norman Bridge of Los Angeles, president of the Board of Trustees, 1896–1917.

High Voltage Research Laboratory, 1923. Built with funds provided by the Southern California Edison Company. Retired in 1959 with basic research completed and rebuilt in 1960 as the Alfred P. Sloan Laboratory of Mathematics and Physics.

Dabney Hall, 1928. The gift of Mr. and Mrs. Joseph B. Dabney of Los Angeles. A major renovation completed in 2004 was made possible by gifts from alumnus Capt. Tyler Matthew; alumnus Roger Davisson and his wife, Marjorie; alumnus William F. Horton and his wife, Glenna Berry-Horton; a distribution from the estate of alumnus George F. Smith; and a collective gift by the Caltech Associates.

William G. Kerckhoff Laboratories of the Biological Sciences: first unit, 1928; second unit, 1939; annex, 1948. The gift of Mr. and Mrs. William G. Kerckhoff of Los Angeles. He was a trustee in 1928.

Guggenheim Aeronautical Laboratory, 1929. Built with funds provided by the Daniel Guggenheim Fund for the Promotion of Aeronautics. A major renovation completed in 2008 was made possible by many private supporters, including Distinguished Alumnus Joe Charyk and his wife, Edwina; Distinguished Alumnus Allen Puckett and his wife, Marilyn; and alumnus Gordon Cann, through his estate.

Athenaeum, 1930. A clubhouse for the teaching, research, and administrative staffs of the Institute and the Huntington Library, Art Collections, and Botanical Gardens, for the Associates of the California Institute of Technology, and for others who have demonstrated their interest in advancing the objectives of the Institute. The gift of Mr. and Mrs. Allan C. Balch of Los Angeles. He was president of the Board of Trustees, 1933–43.

Undergraduate Houses, 1931. With the support of many individuals, including alumni Alexander Lidow, Richard Beatty, and Ray Sidney, these houses were restored. They reopened in 2007.
Blacker House. The gift of Mr. and Mrs. R. R. Blacker of Pasadena.
Dabney House. The gift of Mr. and Mrs. Joseph B. Dabney of Los Angeles.
Fleming House. Built with funds provided by some 20 donors and named in honor of Mr. Arthur H. Fleming of Pasadena, president of the Board of Trustees, 1917–33.
Ricketts House. The gift of Dr. and Mrs. Louis D. Ricketts of Pasadena.

W. K. Kellogg Radiation Laboratory, 1932. The gift of Mr. W. K. Kellogg of Battle Creek, Michigan.

Linde + Robinson Laboratory for Global Environmental Science, 1932 and 2011. The former Henry M. Robinson Laboratory of Astrophysics (1932) was built with funds provided by the International

Education Board and the General Education Board, and named in honor of Mr. Henry M. Robinson of Pasadena, member of the Board of Trustees, 1907–37, and of the Executive Council of the Institute. An extensive renovation transformed the building into the Linde + Robinson Laboratory for Global Environmental Science (2011), renamed in honor of a contribution by Vice Chair of the Board of Trustees and alumnus Ronald K. Linde and his wife, Maxine.

Charles Arms Laboratory of the Geological Sciences, 1938. The gift of Mr. and Mrs. Henry M. Robinson of Pasadena, in memory of Mrs. Robinson's father, Mr. Charles Arms.

Seeley W. Mudd Laboratory of the Geological Sciences, 1938. The gift of Mrs. Seeley W. Mudd of Los Angeles, in memory of her husband.

Charles C. Gates, Jr.–Franklin Thomas Laboratory of Engineering: first unit, 1945; second unit, 1950; complete renovation, 2015. Funds for the first unit were allocated from the Eudora Hull Spalding Trust. The laboratory is named after two devoted stewards of Caltech: Charles C. Gates Jr. (1921–2005), businessman, philanthropist, and longtime Caltech trustee; and Franklin Thomas (1885–1952), civil engineering professor, division chair, and dean of students. The renovation was generously supported by the Gates Frontiers Fund through the vision of Diane G. Wallach and John S. Gates, together with the Fred L. Hartley Family Foundation, James E. Hall (BS '57) and his wife, Sandy, and Li-San Hwang (PhD '65) and his wife, Anne.

Alumni Swimming Pool, 1954. Provided by the Alumni Fund through contributions from the alumni of the Institute.
Scott Brown Gymnasium, 1954. Built with funds provided by the trust established by Mr. Scott Brown of Pasadena and Chicago, who was a member and director of the Caltech Associates.

Norman W. Church Laboratory for Chemical Biology, 1955. Built with funds provided through a gift and bequest by Mr. Norman W. Church of Los Angeles, who was a member of the Caltech Associates.

Eudora Hull Spalding Laboratory of Engineering, 1957. Built with funds allocated from the Eudora Hull Spalding Trust.

Archibald Young Health Center, 1957. The gift of Mrs. Archibald Young of Pasadena, in memory of her husband, who was a life member and officer of the Caltech Associates, 1926–56.

Physical Plant Building and Shops, 1959. Built with funds provided by many donors.

Gordon A. Alles Laboratory for Molecular Biology, 1960. Built with the gift of Dr. Gordon A. Alles of Pasadena, an Institute research associate in biology, an alumnus, and a member of the Caltech Associates, 1947–63; and with funds provided by the National Institutes of Health, Health Research Facilities Branch.

Undergraduate Houses, 1960. Built with funds provided by the Lloyd Foundation and other donors.
Lloyd House. Named in memory of Mr. Ralph B. Lloyd and his wife, Mrs. Lulu Hull Lloyd, of Beverly Hills. He was a member of the Board of Trustees, 1939–52.
Page House. Named in honor of Mr. James R. Page of Los Angeles, a member of the Board of Trustees, 1931–62, and chairman, 1943–54.
Ruddock House. Named in honor of Mr. Albert B. Ruddock of Santa Barbara, a member of the Board of Trustees, 1938–71, and chairman, 1954–61.

Harry Chandler Dining Hall, 1960. The gift of the Chandler family, the Pfaffinger Foundation, and the Times Mirror Company of Los Angeles.

W. M. Keck Engineering Laboratories, 1960. The gift of the W. M. Keck Foundation and the Superior Oil Company of Los Angeles.

Alfred P. Sloan Laboratory of Mathematics and Physics, 1960. Formerly the High Voltage Research Laboratory, 1923. Rebuilt in 1960 with funds provided by the Alfred P. Sloan Foundation.

Graduate Houses, 1961:
Braun House. Built with funds provided by the trustees of the Carl F Braun Trust Estate, in his memory.
Marks House. The gift of Dr. David X. Marks of Los Angeles.

Kármán Laboratory of Fluid Mechanics and Jet Propulsion, 1961. The gift of the Aerojet-General Corporation, named in honor of Dr. Theodore von Kármán, professor of aeronautics at the Institute, 1929–49.

Firestone Flight Sciences Laboratory, 1962. The gift of the Firestone Tire and Rubber Company.

Winnett Student Center, 1962. The gift of Mr. P. G. Winnett of Los Angeles, a member of the Board of Trustees, 1939–68. Winnett houses the Caltech Store, the Red Door Café, and Caltech Wired.

Beckman Auditorium, 1964. The gift of Dr. Arnold O. and Mabel Beckman of Corona del Mar. The late Dr. Beckman, an alumnus, was an Institute faculty member from 1928 to 1939. He joined the Board of Trustees in 1953, was chairman, 1964–74, and was chairman emeritus until his death in 2004.

Harry G. Steele Laboratory of Electrical Sciences, 1965. Built with funds provided by the Harry G. Steele Foundation and the National Science Foundation.

Central Engineering Services Building, 1966.

Robert A. Millikan Memorial Library, 1967. Built with a gift from Dr. Seeley G. Mudd and named in honor of Dr. Robert Andrews Millikan, director of the Bridge Laboratory of Physics and chair of the Executive Council of the Institute, 1921–45.

Arthur Amos Noyes Laboratory of Chemical Physics, 1967. Built with funds provided by the National Science Foundation and Mr. Chester F. Carlson, an alumnus, and named in honor of Dr. Arthur Amos Noyes, director of the Gates and Crellin Laboratories of Chemistry and chair of the Division of Chemistry and Chemical Engineering, 1919–36.

Central Plant, 1967.

George W. Downs Laboratory of Physics and Charles C. Lauritsen Laboratory of High Energy Physics, 1969. The Downs wing was built with funds provided by Mr. George W. Downs and the National Science Foundation. The Lauritsen wing was built with Atomic Energy Commission funds and named in honor of Dr. Charles C. Lauritsen, a member of the Institute faculty, 1930–68.

Keith Spalding Building of Business Services, 1969. Named in honor of Mr. Keith Spalding, Caltech trustee, 1942–61.

Donald E. Baxter, M.D., Hall of the Humanities and Social Sciences, 1971. Built with funds provided by Mrs. Delia B. Baxter of Atherton and named in honor of her late husband, Donald E. Baxter, M.D. Additional funds were given by the U.S. Department of Health, Education and Welfare. Dr. and Mrs. Simon Ramo provided funds for the completion of **Ramo Auditorium** within the hall. Dr. Ramo is a life member of the Board of Trustees.

The Earle M. Jorgensen Laboratory of Information Science, 1971. Built with the gift of Mr. and Mrs. Earle M. Jorgensen, with additional funds provided by the Booth-Ferris Foundation and other private donors. Mr. Jorgensen was a member of the Board of Trustees, 1957–99. A full remodeling of the building was completed in June 2012 through funding provided by the Joint Center for Artificial Photosynthesis/Department of Energy, Lynda and Stewart Resnick through the Resnick Sustainability Institute, Gordon and Betty

Moore and the Gordon & Betty Moore Foundation, the Ahmanson Foundation, and the Provost's Office.

The Mabel and Arnold Beckman Laboratories of Behavioral Biology, 1974. The gift of Dr. Arnold O. and Mabel Beckman of Corona del Mar. The late Dr. Beckman was chairman emeritus of the Board of Trustees.

Seeley G. Mudd Building of Geophysics and Planetary Science, 1974. Built with funds provided by Dr. Seeley G. Mudd, Mrs. Roland Lindhurst, Mr. and Mrs. Ross McCollum, Mr. and Mrs. Henry Salvatori, and the U.S. Department of Health, Education, and Welfare.

Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory, 1981. Built with funds allocated from the Clifford S. and Ruth A. Mead Memorial Building Fund.

Thomas J. Watson, Sr., Laboratories of Applied Physics, 1982. Built with funds provided by the Watson family and other private donors. Thomas J. Watson, Jr., was a member of the Board of Trustees, 1961–92.

Braun Laboratories in Memory of Carl F and Winifred H Braun, 1982. Built with funds provided by the Braun family, other private donors, and the National Cancer Institute. Various members of the Braun family have served on Caltech's Board of Trustees.

Parsons-Gates Hall of Administration, 1983. Formerly Gates Laboratory of Chemistry, 1917. Rebuilt in 1983 with funds provided by the Ralph M. Parsons Foundation and the James Irvine Foundation.

Athletic Facility, 1984. Built with funds provided by the Carl F Braun Trust and the Braun Foundation.

Catalina Graduate Apartment Complex, 1984, 1986, 1988. Four of the buildings have been named for Max and Ruth Alcorn, Frank and Elizabeth Gilloon, Fred and Marvis Maloney, and William C. and Verna Rockefeller, honoring their generosity to Caltech.

Infrared Processing and Analysis Center, 1986. Renamed the **David W. Morrisroe Astroscience Laboratory,** 1995. Second-floor addition built with funds provided by the late Dr. Arnold O. Beckman, chairman emeritus of the Board of Trustees.

Wilson Avenue North Parking Structure, 1987.

Beckman Institute, 1989. Built with funds provided by the Arnold and Mabel Beckman Foundation and other private donors. The late Dr. Arnold O. Beckman was chairman emeritus of the Board of Trustees.

Braun Athletic Center, 1992. Built with funds provided by the Braun family.

Holliston Avenue Parking Structure/Satellite Utility Plant, 1993.
The Gordon and Betty Moore Laboratory of Engineering, 1996. Built with funds provided by Dr. and Mrs. Gordon Moore. Dr. Moore is an alumnus, and a chairman emeritus of the Board of Trustees. Betty Moore is an honorary life trustee.

Avery House, 1996. Built with funds provided by Mr. R. Stanton Avery, who was a member of the Board of Trustees from 1971 until his death in 1997. He had been chairman, 1974–85, and chairman emeritus since 1986.

Sherman Fairchild Library of Engineering and Applied Science, 1997. Built with funds provided by the Sherman Fairchild Foundation.

Space Infrared Telescope Facility Science Center, 1998. Renamed the **Spitzer Space Telescope Science Center**, 2003. Located within the **Keith Spalding Building of Business Services.**

Powell-Booth Laboratory for Computational Science, 1999. Formerly the Willis H. Booth Computing Center, 1963, constructed with support from the Booth-Ferris Foundation and the National Science Foundation. Renovated in 1999 with grants from the Charles Lee Powell Foundation, the National Science Foundation, and the Booth-Ferris Foundation.

Wilson Avenue South Parking Structure, 1999.

Center for Student Services, the Keck Wing, 2000. Originally the Keck Graduate House, built with funds provided by the William M. Keck, Jr., Foundation, 1961.

Center for Student Services, the Mosher-Jorgensen Wing, 2002. Originally the Mosher-Jorgensen Graduate House, built with funds provided by Mr. Samuel B. Mosher and Mr. Earle M. Jorgensen, both of Los Angeles. Mr. Jorgensen was a member of the Board of Trustees, 1957–99.

Financial Services Building, 2000.

Broad Center for the Biological Sciences, 2002. Made possible by a lead gift from Eli and Edythe Broad. Eli Broad is a member of the Board of Trustees.

California Parking Structure, 2005.

Cahill Center for Astronomy and Astrophysics, 2009. Made possible by a lead gift from Charles Cahill in honor of his late wife, Aníko Dér Cahill, and by gifts from trustee and alumnus Fred Hameetman and his wife, Joyce, alumnus Michael Scott, and other private individuals and foundations.

Walter and Leonore Annenberg Center for Information Science and Technology, 2009. Built with a lead gift from the Annenberg Foundation and with funds provided by Life Trustee Stephen Bechtel, Jr., and other private donors.

Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering, 2010. Built with funds provided by alumnus Warren Schlinger and his wife, Katharine, a former Caltech employee, along with other private donors.

W. M. Keck Center, 2013. The Keck Center is the home of the Keck Institute for Space Studies (KISS) and features conference meeting room space suitable for the Caltech Board of Trustees, incorporating the historic Tolman-Bacher House within the grounds. The 2013 renovation/construction project was supported with funds from the W.M. Keck Foundation and Caltech.

Caltech Childcare Center, 2014. The Caltech Childcare Center is a new facility located on the South Campus to provide day care space for children of the Caltech community.

Off-Campus Facilities

William G. Kerckhoff Marine Biological Laboratory, 1930, Corona del Mar. Rehabilitated with funds provided by the National Science Foundation in 1966.

Jet Propulsion Laboratory (JPL), 1944, 4800 Oak Grove Drive, Pasadena. Administered by the Institute; owned and supported by the National Aeronautics and Space Administration.

Palomar Observatory, 1948, San Diego County. Site of the 200-inch Hale Telescope (1948) and the 48-inch Schmidt telescope (1949), built by the Institute with funds from the Rockefeller Foundation. The Schmidt was named the Samuel Oschin Telescope in 1987 in honor of benefactor Samuel Oschin of Los Angeles.

Owens Valley Radio Observatory, 1958, Big Pine. Built with funds provided by the Winnett Foundation, the Office of Naval Research, the National Science Foundation, and the Oscar G. and Elsa S. Mayer Charitable Trust.

Big Bear Solar Observatory, 1969, Big Bear Lake. Built with funds provided by the National Science Foundation and the Max C. Fleischmann Foundation of Nevada. (Operated by the New Jersey Institute of Technology.)

Caltech Submillimeter Observatory (CSO), 1986, Mauna Kea, Hawaii. Built with funds provided by the National Science Foundation and the Kresge Foundation.
W. M. Keck Observatory, Keck I (1991), Keck II (1996); Mauna Kea, Hawaii. Built with funds provided by the W. M. Keck Foundation. Site of the two 10-meter Keck Telescopes.

Georgina and William Gimbel Building, Caltech Submilli-meter Observatory, 1996, Hilo, Hawaii. Built with funds provided by Mr. and Mrs. William Gimbel, members of the Caltech Associates.

Laser Interferometer Gravitational-Wave Observatory (LIGO), 1999, Hanford, Washington, and Livingston, Louisiana. Built with funds provided by the National Science Foundation.

Beckman Institute

Opening its doors in 1990, the Beckman Institute has been a major addition to Caltech. The mission of the scientists working there is to invent new methods, materials, and instrumentation for fundamental research in biology and chemistry that will open the way for novel applications of scientific discoveries to human needs.

Caltech Center for Diversity (CCD)

The Caltech Center for Diversity (CCD) is responsible for the campus' initiatives associated with access, equity and inclusion and campus-wide inclusive excellence. The CCD provides programs and services that meet the specific needs of Women, Lesbian, Gay, Bisexual, Transgendered and Gender Queer/Questioning (LGBTQ), Underrepresented and Ally communities on campus. The CCD's stated mission is to:

- Promote and provide access to admission information and campus resources;
- Support activities that enhance the inclusion of women, under-represented, underserved and minorities (URM) and lesbian, gay, bi-sexual, transgender and questioning (LGBTQ) in all aspects of campus life; and
- Collaborate with the Caltech community and student affairs support services (both on and off campus) to ensure students are actively engaged and able to access resources that help them achieve their academic and personal goals and ultimately graduate from Caltech.

The Center provides oversight and support for clubs and associations focused on diversity in science and engineering such as the Society of Hispanic Professional Engineers (SHPE), National Society of Black Engineers (NSBE), Society of Women Engineers (SWE) and participation in the National Organization of Gay, and Lesbian Scientists and Technical Professionals, Inc. (NOGLSTP). If you are interested in getting involved with CCD activities please check the center website (www.diversitycenter.caltech.edu).

Center for Data-Driven Discovery

The mission of the Center for Data-Driven Discovery (CD3) is to assist Caltech researchers with the projects that are data-intensive and computational in nature. It is a part of a joint initiative on "data science" with the Center for Data Science and Technology at JPL.

The central focus of CD3 is the methodologies for handling and analysis of large and complex data sets, in facilitating the data-to-discovery process. It is about applications of data-driven computing in various scientific domains, such as biology, physics, astronomy, geophysics, etc.

CD3 also serves as a catalyst for new collaborations and projects between different scientific disciplines, and between the campus and JPL. Of a particular interest is the sharing and transfer of methodologies, where the solutions from one field can be reapplied in another one. The scientific staff of the Center has an expertise that spans various aspects of computational science, and works on a collaborative basis with research groups on the campus and at JPL, in helping develop novel, exploratory projects, and in the execution of larger, funded projects that involve data-intensive computing.

The Center also helps in the development of educational materials for training students in the research skills that are increasingly necessary for data-rich science in the 21st century.

Center for Teaching, Learning, & Outreach (CTLO)

The Center for Teaching, Learning, & Outreach (http://teachlearn.caltech.edu) offers programs and services in support of Caltech's multifaceted educational efforts, including undergraduate and graduate courses and curricula, formal and informal learning, and educational outreach partnerships with K-12 teachers and students. With a commitment to evidence and innovation, CTLO focuses on:

- Instructor Support: Providing support for effective course design and teaching methods to university faculty and teaching assistants (TAs). Topics regularly addressed through individual consultations, training programs, workshops, and courses, include in-class techniques, choice and use of instructional technologies, feedback on teaching, and research on teaching in the disciplines.
- Student Learning: Fostering opportunities for students to grow as teachers, mentors, and leaders. CTLO oversees the Caltech Project for Effective Teaching (CPET), a graduate student group offering seminars on teaching and learning, as well as the Certificates of Interest and Practice in University Teaching, and collaborates with the undergraduate Academics and Research

Committee (ARC) on course video capture, course ombuds, and other initiatives.

- Educational Outreach: Helping faculty and students in developing K-12 outreach programs, including collaborations with schools and districts in Pasadena and Greater Los Angeles. CTLO assists faculty with funding proposals with educational components, convenes educational outreach coordinators from across Caltech's divisions, and runs several signature Caltech educational outreach programs, such as Summer Research Connection and Community Science Academy.

Hixon Writing Center (HWC)

The Hixon Writing Center (HWC) at the California Institute of Technology promotes excellence in writing and communication. The HWC operates on the premise that writing is a mode of discovery and learning as well as a tool for communication, and thus strong writing skills are fundamental to inquiry, learning, and success across disciplines.

The HWC works actively with Caltech students, faculty, and the Caltech community. The HWC offers students the opportunity to meet with professional and peer tutors to discuss works-in-progress; these sessions help students accomplish short-term goals while they also promote the acquisition of skills that are valuable for long-term success. The HWC regularly holds presentations and workshops on communication-related topics that interest our students. HWC staff members are available to consult with Caltech faculty and TAs about best practices for incorporating, designing, and responding to writing assignments in courses across all disciplines. Finally, the HWC sponsors events and creates resources that support campus-wide discussions about the roles writing and communication play in teaching, learning, and research in science and engineering.

The HWC is a part of the division of Humanities and Social Sciences, and it is funded in part by a generous donation from Alexander P. and Adelaide F. Hixon. The HWC is open during the academic school year, and more information is available at writing.caltech.edu.

LIBRARIES

The Caltech Library helps enable the Institute fulfill its mission to expand human knowledge through research integrated with education. The Library maintains extensive electronic and print collections, a variety of study spaces, and a user-focused program of instruction and outreach to support student success at Caltech. Visit the Library's website, library.caltech.edu, to search library collections, access research guides, and get additional information about the library.

The Sherman Fairchild Library (SFL) is the main library on campus. SFL is complemented by three branch libraries: Humanities and

Social Sciences (Dabney), Astrophysics (Cahill), and Geology (North Mudd). SFL is open 24/5 (24/7 during exam weeks), and offers a range of collaborative and private study spaces including five bookable group study rooms and a new TechLab with 3D printers and scanners. Laptops, kindles, electronic kits and more can be borrowed through the Library's edevice lending program. All textbooks assigned for courses are available for short-term use through the Library's Course Reserves service.

The Library's Interlibrary Loan staff, located on the first floor of Millikan Memorial, can obtain books and articles not owned by Caltech Library at no charge to the requester and typically within 24 hours or less. A flexible collaboration and study space with large displays is available on the 9th floor of Millikan.

The Library's digital repository of research by Caltech authors includes CaltechTHESIS, where student work is preserved and made discoverable to Internet search engines. The Library also offers a binding service for student-authored works (PODS).

Archives and Special Collections

The Caltech Archives and Special Collections constitute rare and unique materials, and serve as the collective memory of the California Institute of Technology. We collect, organize, preserve and make accessible the institutional records, personal papers, documents, photographs, oral histories, historic apparatus and artifacts, and audiovisual media that tell the Institute's history. Among the over 300 manuscript collections can be found the personal and professional papers of 13 Nobel Prize winners and 14 National Medal of Science recipients. Our photo collection is comprised of over 10,000 photos that can be viewed online, as well as thousands more.

These research collections are available to the campus community for instructional and research purposes, as well as to qualified non-campus users by appointment. A collection overview and other pertinent information is available at our website, www.archives.caltech.edu. Our Reading Room hours are Monday through Friday, 8:30 am to 4:00 pm. All who wish to visit the Caltech Archives are requested to phone or write ahead to be sure of staff assistance and space availability.

UNDERGRADUATE RESEARCH

The Institute offers the opportunity for qualified students to engage in research early in their careers under the supervision of a faculty member. There are four principal avenues for undergraduate research: the senior thesis, the Summer Undergraduate Research Fellowships (SURF) program, research courses for academic credit, and research for pay under a faculty member's grant or contract. Students may combine these options but may not receive both pay and credit at the same time for the same piece of work.

The senior thesis involves original research under the mentorship of a faculty member, then documenting the methodology and accomplishments in scholarly form, and finally oral presentation of the results to an examination committee. This integrated effort develops research, writing, and presentation skills that together provide an excellent preparation for future graduate studies and/or professional life. Since senior thesis requirements vary by option, individual option representatives should be consulted.

The Summer Undergraduate Research Fellowships (SURF) program provides continuing undergraduate students the opportunity to work on an individual research project in a tutorial relationship with a mentor, usually a member of the Caltech/JPL research community, but occasionally a faculty member at another college or university. Students write research proposals in collaboration with their mentors. Proposals and recommendations are reviewed by the SURF administrative committee, and awards are made on the basis of reviewer recommendation and available funding. The work is carried out during a 10-week period in the summer. Students may attend weekly seminars presented by members of the Caltech faculty and JPL technical staff and may participate in professional development workshops. At the conclusion of the summer, SURFers submit a written report describing the project, methods, and results of their work. On the third Saturday of October, students make oral presentations of their projects at SURF Seminar Day. About 20 percent of the students publish their work in the open scientific literature. In 2015, SURF students received awards of $6,000. Applications are available online at http://www.surf.caltech.edu and are due in mid-February. Awards are announced in early April. To be eligible, students must be continuing undergraduates and have a cumulative GPA of at least 2.0. Students must complete the third quarter at Caltech (or at another school under a program approved by a dean). Students must be eligible for fall term registration as of the end of the June Undergraduate Academic Standards and Honors (UASH) Committee reinstatement meeting and must not be on medical leave or under disciplinary sanction. For further information regarding this program, contact the Student-Faculty Programs Office, 330 Center for Student Services, (626) 395-2885, sfp@caltech.edu. Visit the Student-Faculty Programs website at http://www.sfp.caltech.edu.

Most options also offer undergraduate research courses in order to encourage research participation; students should consult listings and descriptions of opportunities. Students registering for a research course during the summer do not have to pay tuition.

STUDENT LIFE

Undergraduate Student Houses

Seven of the eight undergraduate student houses are situated on both sides of the Olive Walk near the southeastern end of the campus.

The original four—Blacker, Dabney, Fleming, and Ricketts—were built in 1931 from the plans of Mr. Gordon B. Kaufmann, in the Mediterranean style to harmonize with the adjacent Athenaeum. The other three, designed by Smith, Powell and Morgridge, were completed in 1960, and are named Lloyd, Page, and Ruddock.

Each of the houses is a separate unit with its own dining room and lounge, providing accommodations for between 65 and 100 students, depending on the house. Each has its own elected officers; a long history of self-governance gives students a great deal of influence over their living environments. There are three undergraduate Residential Life Coordinators (RLCs) in campus housing, situated in different houses. An RLC is a specially trained full-time university employee, specializing in college student development, community building, counseling, and crisis intervention. The RLCs supervise the Resident Associates (RAs) on programming and overall student wellness. The RLCs also assist Housing with the management and daily operations of the houses. Each house has one or more Resident Associates, who are typically graduate students. In addition to the student houses, the Institute maintains three apartment buildings, Marks/Braun House, and a number of houses on campus property. Typically two or three students share an apartment. Depending upon size, the off-campus houses have a capacity of four to ten students. These residences are all within a short walk of the campus and offer students greater privacy, a different lifestyle, and the opportunity to prepare their own meals.

Mail is delivered daily to the student mailboxes. Students should use their mailbox number, California Institute of Technology, Pasadena, CA 91126, to facilitate handling of mail at the campus post office.

For more information, please visit www.housing.caltech.edu.

Avery House

Made possible by a gift from trustee R. Stanton Avery, this innovative residential complex was designed by Moore, Ruble, Yudell and completed in September 1996. Located at the north end of the campus, Avery House has a Residential Life Coordinator, two Resident Associates, two faculty apartments and rooms for about 136 undergraduates. Its dining facilities, meeting rooms, lounges, and library are designed to encourage informal faculty-student interaction and to attract all members of the campus community to join in this interaction. Avery House hosts programs and social events that facilitate involvement between residents, and faculty in residence.

The Student Activities Center

The SAC is located in the basement of the south undergraduate housing complex and is open for student use 24 hours a day. The SAC provides office space for the officers of the undergraduate student government, working space for student publications, rehearsal space for musical activities, and space for many other student-oriented functions.

Whether students are interested in music, publications, student government, gaming, photography, or simply finding a room for their group to meet in, the SAC will probably have what is needed. The center also houses the South House laundry room and has several club rooms, a small library, a shop, and a movie screening room—most are open 24 hours.

Faculty-Student Relations
Faculty-student coordination and cooperation with regard to campus affairs are secured through the presence of students on faculty committees, by faculty-student conferences, and by other mechanisms.

Freshman Advisers
Each member of the freshman class is assigned a faculty advisor and is a member of a small advising group. The adviser follows the freshman's progress and provides advice on any questions or problems that the freshman may have.

Option Advisers
Each member of the three undergraduate upper classes is assigned an option adviser, a faculty member in the option in which the student is enrolled. The adviser takes an interest in the student's selection of courses and progress toward a degree, and, eventually, in assisting the student toward satisfactory placement in industry or in graduate school. Normally, the association between student and adviser is established before the beginning of the sophomore year and continues through graduation.

Athletics, Physical Education & Recreation (APER)
Caltech supports an extensive program of competitive athletics. As a member of NCAA Division III and the Southern California Intercollegiate Athletic Conference, Caltech participates in intercollegiate competition in nine men's and eight women's sports. All teams compete during a regular season to qualify for the conference tournament in their respective sport. Individual student-athletes and teams distinguishing themselves can earn the privilege of participating in NCAA regional and national championships.

Caltech also sponsors vigorous club sports programs and intramural competition. Club sports include Ultimate Frisbee, volleyball, badminton and soccer. Intramural competitions are contested by residence house teams in several sports, including soccer, dodgeball, kickball, Ultimate Frisbee, basketball, volleyball, and floorball. Approximately 25 percent of Caltech undergraduates participate in intercollegiate athletics and over 80 percent participate in some form of organized athletic competition each year.

Outdoor athletic facilities include an all-weather running track, a soccer field, a baseball diamond, eight tennis courts, and two 25-yard, eight-lane swimming pools. Indoor facilities include two full-size gymnasiums for basketball, volleyball, table tennis, fencing and badminton; four racquetball courts; two squash courts; a 5,000-square-foot weight room and more than 55 pieces of cardio-respiratory equipment, including treadmills, exercise bikes and ellipticals; and a large multipurpose room for dance/aerobics, martial arts and a variety of group fitness courses.

The department is also responsible for management of Caltech's recreation programs and physical education curriculum.

More information can be found at GoCaltech.com

Interhouse Activities

The president of each undergraduate house represents that house on the Interhouse Committee (IHC), which handles any matters affecting the houses in general. The IHC works in conjunction with the APER department to conduct intramural competitions as described above and conducts its own Discobolus Trophy competition, in which a house may challenge the house holding the trophy to a mutually agreed upon contest.

ASCIT

The undergraduate student body forms the membership of a corporation known as the Associated Students of the California Institute of Technology, Inc., or ASCIT. Governed by a board of directors consisting of nine elected officers, it is involved in many aspects of student life, overseeing publication of the student newspaper, a directory, the yearbook, a research-opportunities handbook, a course review, and a literary magazine.

Besides overseeing many student publications and coordinating activities and policies, the ASCIT Board of Directors administers the corporation's finances. ASCIT sponsors a wide variety of special-interest clubs and programs, such as the student shop and the Students for the Exploration and Development of Space (SEDS).

The student government is active in campus affairs. The student members of each standing faculty committee ensure that undergraduate opinion is considered seriously. Excellent informal relations between students and faculty and between students and administration promote discussion of mutual concern and goodwill. Student-faculty conferences are held every other year and serve a very useful purpose to promote cooperation and communication.

Graduate Student Council

The Graduate Student Council (GSC) is the governing body for all graduate students at Caltech. The GSC provides funding for student clubs, publishes newsletters, and organizes and subsidizes various campus events and programs. For example, the GSC sponsors events for new students, hosts a graduate student formal, honors teaching and mentoring at Caltech and helps facilitate the Everhart Lecture Series, a series of lectures for outstanding graduate student researchers and presenters. Students interested in getting involved with, or contacting the GSC, please check the Graduate Student Council website.

Honor System

The Honor Code, embodied in the phrase "No member shall take unfair advantage of any other member of the Caltech community," is the fundamental principle of conduct for all students and extends to all phases of campus life, including scholastic and extracurricular activities, relations among students, and relations between students and faculty. The Honor System is the most important tradition of the undergraduate student body. The Board of Control, which is composed of elected student representatives, is charged with monitoring the academic Honor System for undergraduates, investigating course work violations, and making recommendations to the Dean of Undergraduate Students. The Conduct Review Committee, composed of students, faculty and staff, hears cases involving non-academic Honor System and Institute policy violations for undergraduate students, and also makes recommendations to the Dean. At times the Undergraduate Dean of Students, or his/her designee, also considers cases involving the Honor System and Institute Policies for undergraduate students.

The Honor System is also an important part of graduate student life. The Graduate Honor Council (GHC)is the body responsible for reviewing alleged honor code violations with respect to coursework. The GHC investigates and hears a case, then forwards its recommendations to the Dean of Graduate Studies for final review and decision. The GHC consists of Co-Chairs and Honor Council Board Members. All Members of the Graduate Honor Council must be in good standing with the Office of Graduate Studies and must attend a formal training before they may serve on a case. Examples of honor code violations include, but are not limited to, plagiarism, violations of the collaboration policy in a class and/or using resources that were strictly prohibited for homework and or exams. Incidents that are not handled by the GHC include accusations of research misconduct, which are handled by the Office of Research Compliance; grade disputes, which are handled by the Office of the Provost; and Institute Policy violations which are handled by the Office of the Dean of Graduate Studies or the appropriate administrative organization.

Student Body Publications

The publications of the student body include a weekly paper, *The California Tech*; an undergraduate research journal, *CURJ*; a literary magazine, *The Totem*; a student handbook, *the little t,* which gives a survey of student activities and organizations and serves as a campus directory; a yearbook, *The Big T*; an annual review of the quality of teaching in the various courses, and an undergraduate research opportunities handbook, *UROH*. These publications, staffed entirely by students, provide an opportunity for interested students to obtain valuable experience in creative writing, photography, artwork, reporting and editing, advertising, and business management.

Performing and Visual Arts

Performing and Visual Arts The Institute provides directors and facilities for choirs, concert band, jazz band, symphony orchestra, numerous chamber music ensembles, guitar classes, a theater program, ceramics and visual arts classes. These activities are centered in the Music and Theater Arts houses on Hill Avenue along the eastern edge of campus. Rehearsals and performances are held mainly in Dabney Lounge and Ramo Auditorium.

Student Societies and Clubs
The Institute has more than 90 societies and clubs covering a wide range of interests. The American Chemical Society, the American Institute of Chemical Engineers, the American Society of Mechanical Engineers, and the Society of Women Engineers all maintain active student branches. There is a chapter of the National Society of Black Engineers, and the Caltech Latino Association of Students in Engineering and Science is a chapter of the Society of Hispanic Engineers.

The Institute has a chapter (California Beta) of Tau Beta Pi, the national scholarship honor society of engineering colleges. Each year the Tau Beta Pi chapter elects to membership students from the highest-ranking eighth of the junior class and the highest fifth of the senior class.

Special interests and hobbies are provided for by a broad and constantly changing spectrum of clubs, some informal but most formally recognized by Caltech through either ASCIT or the Graduate Student Council.

Student Shop
The student shop is located in the Physical Plant complex. It is equipped by the Institute, largely through donations, and is operated by students. Qualified students may work on private projects that require tools and equipment not otherwise available. All students who have completed an appropriate machine shop training course are eligible to apply for membership in the student shop. Instruction on specific machines and tools can be provided as needed. Yearly dues are collected for maintenance and tool replacement.

The Caltech Y
The Caltech Y is a unique nonprofit organization on campus. Founded by students for students, the Y challenges the Caltech community to see the world with a broader perspective and a deeper understanding of social issues. Through community service projects, outdoor adventures, social activities, and cultural events, the Y encourages students to become active participants during their years here. The Caltech Y helps students plan events, meetings, and initiatives on campus and provides the resources and equipment needed for successful programs. Some of the many Y-sponsored activities include the Y hike in the California Sierras, Alternative Spring Break, Make-a-Difference-Day, World Fest, the Social Activism Speaker Series, and the D.C. Science Policy Trip. The Y also provides services to the Caltech community, such as low-cost rentals on camping equipment, discounted tickets, and much more.

Religious Life

In addition to several groups active on campus, such as the Caltech Christian Fellowship, the Newman Center, and Hillel, houses of worship of many different denominations are within walking distance or are only a short drive from campus.

Public Events

Beckman and Ramo Auditoriums serve as the home of the professional performing arts programs on the Caltech campus. Each year, more than 50 lectures, outreach programs, performing arts events, and films are presented at Caltech. Tickets, often with discounts available, are offered to Caltech students for all events in Beckman and Ramo Auditoriums. Visit www.events.caltech.edu for more information.

Caltech Store

The Caltech Store is located on the ground floor of the Winnett Student Center. Owned and operated by the Institute, the store serves the students, faculty, and staff, carrying a stock of Caltech authors' books and other books, insignia merchandise, gift items, and school supplies. Located within the store are the Red Door Café and Caltech Wired computer store. The Red Door Café provides various types of coffee drinks and juices, along with other food items. Caltech Wired provides computers (including hardware and supporting software and instructional materials) that support Caltech's educational and research functions.

STUDENT HEALTH

Health Form

Prior to initial registration, each admitted student is REQUIRED to submit a completed Health Form that includes medical and immunization history and a physical examination. The Health Form is sent as part of the Orientation Packet at the time of notification of admission for incoming freshmen, and accepted graduate students are notified by e-mail to visit the Health Center website at http://www.healthcenter.caltech.edu to download the health form.

Student Health Services

ALL enrolled students can use the Health Center irrespective of the insurance they have. Enrolled students pay a health fee each semester to access the Health Center.

The Archibald Young Health Center provides the following services (1) clinic consultation and treatment of most medical problems by physicians and nurse practitioners (physician visits by appointment only and at prescribed hours); (2) referral to specialists; (3) laboratory test and some radiology test as ordered by the medical staff; (4) women's health services, including annual pap and contraceptive needs; (5) sexual health concerns, including STI screening; (6) prescription services for most medications and common vaccinations; (7) allergy injection services.

Spouses of students may enroll in our Spousal Program to access these same services once paying the Spousal Program fee. For more information about the Spousal Program, call the Health Center. A variety of health education handouts are also available. For more information, visit the Health Center's website at http://www.healthcenter.caltech.edu or call the clinic at 626-395-6393.

Student Health Insurance
Students have the option to waive Caltech's medical coverage provided they show proof of adequate coverage. The Caltech student health plan covers (with deductible and copay) hospital and surgical costs, as well as the cost of outpatient treatment for injury, illness, and psychotherapy. Students may continue coverage under the Caltech student health plan during the entire time they are enrolled as degree-seeking Caltech students. No matter what insurance you have as an enrolled student you may use the Health and Counseling Center.

CAREER DEVELOPMENT

Career Services
The Career Development Center (CDC) provides assistance to students in the areas of career planning and employment. Assistance is available in areas such as career choice, résumé preparation, interviewing, graduate school application, and job search strategies. Career and vocational interest tests can also be taken on the recommendation of one of the career counseling staff members.

General Information
All students are encouraged to visit and make use of the Career Development Center early in their student careers.

Walk-In Counseling
Several days a week, students can "walk in" to consult with a career counselor without an appointment. This allows students to deal with time-sensitive or quickly answered concerns without having to make an appointment.

CDC Online and the CDC Library
The CDC's website contains information about the center's programs and activities, as well as links to career, educational, and employment resources nationwide (http://www.career.caltech.edu). Students can schedule appointments for career counseling, register and post resumes for online recruiting, view work-study or tutoring job postings online. The CDC library contains information on graduate, and professional schools, employers, career options and job hunting skills.

Graduate and Professional School Advising
The CDC provides advice on applying to Ph.D. and master's programs in the sciences or applied sciences, economics, medicine,

public health, environmental sciences, business, law, and other fields. Workshops and individual advising are available on the graduate school admissions process, essay writing, and related topics. The CDC's library and website have helpful resources.

Pre-Health Careers Advising
Students planning to apply to medical, dental, veterinary, or pharmaceutical graduate school have access to a wide range of advising services through the CDC. Students can obtain relevant medical research experience through the Caltech summer preceptorship program, which has placements with hospitals in the LA area. The pre-health advisor is available to work with students throughout the process from freshman year to graduation.

Students planning to apply to graduate school or professional graduate degrees are encouraged to plan ahead and to utilize the resources of the CDC in making choices about and implementing choices related to graduate studies.

On-Campus Recruiting Program
Through the on-campus recruiting program, employment interviews Arearranged by the CDC with companies that seek full-time employees pursuing B.S., M.S., Eng., or Ph.D. degrees. Many firms also recruit students for summer internships or jobs. All students, Caltech postdoctoral scholars, and recent alumni are eligible to participate.

Career Fairs
Each year two career fairs are organized by the CDC and held in October and January.

A diverse range of companies send representatives to campus to talk to Caltech undergraduates, graduate students, and postdoctoral scholars about permanent employment, summer jobs, or internship opportunities with students. Many firms hold information sessions and conduct on-campus interviews.

Work-Study and Employment Listings
Job listings are maintained in the Career Library and through Techerlink Network for students seeking full-time, part-time (including tutoring positions), or work-study employment. Part-time employment provides students with the opportunity to help finance their education and to gain relevant work experience. One popular online resource is Caltech's tutoring service, through which Caltech students are hired to work as paid tutors for students attending high school in the local area. (See also the student employment section on page 204.)

Summer Internships and Jobs
Students are encouraged to establish a relationship with the CDC staff during the fall term to start the summer job process.

The CDC website has a special section on internships, many firms recruit on campus or at the career fairs for interns, or list positions on Techerlink, the CDC online job listing resource. Students may wish to confer with a career counselor to develop a plan to find summer work that will support or complement long-term career objectives. The CDC provides job-search assistance, including résumé preparation advice, mock interview training, and advice on evaluating job offers. Many employers, eager to hire Caltech students, provide or supplement transportation and housing as part of their summer employment package.

Employment Experience of Recent Graduates
Each year the CDC surveys graduating students' future plans. Over several years, approximately 50 percent of undergraduates are accepted to graduate school programs, 30 percent accept employment, 10 percent have not accepted offers yet, and 10 percent pursue unconventional options, such as part-time work, part-time school, travel, a year off, etc. At the M.S. level, about 85 percent continue in graduate school, and the remainder accept employment. Of those receiving the Ph.D. degree, about 50 percent accept postdoctoral, faculty or other academic/research positions, about 40 percent accept positions outside of academia, and 10 percent pursue other options.

CALTECH ALUMNI ASSOCIATION

The mission of the Association is to promote the interests of Caltech in setting a world standard of academic excellence by strengthening the ties of goodwill and communication between the Institute, its alumni, and current students, and by maintaining programs to serve alumni needs. With 23,000 graduates, Caltech's relatively small alumni community has an outsized influence on science, business, and culture around the world. Membership in the Caltech Alumni Association can help you access the full potential of this unparalleled network.

Our programs and services include:

- Access to the Alumni Network, with resources to help you connect with alumni and support your career development;
- Reunion Weekend, an annual four-day event with nearly 80 activities, including thought-provoking lectures, private tours, house reunions, social events, and more;
- Seminar Day, where alumni and their guests are given a front-row seat to the latest research and discoveries taking place on campus;
- Alumni College, a one-day lecture series drawing Caltech faculty together to explore a theme or subject;
- Regional Events that bring the best of Caltech to your area, featuring presentations from Caltech faculty, exclusive tours, career networking opportunities, social events, and more;
- Travel/lifelong learning programs worldwide.

Additional benefits of membership include a subscription to

Engineering & Science magazine, discounts at the Caltech Bookstore, and more. For more, visit alumni.caltech.edu.

INTERNATIONAL STUDENT PROGRAMS

As the definitive immigration resource for international students, International Student Programs (ISP) is responsible for advising students on all immigration-related matters, such as visa acquisition, employment authorization, extensions of stay, and more. In addition, ISP provides programs that assist international students and their dependents in adjusting to life in the United States. ISP plans and promotes events that celebrate international education and cultures of the world, address cross-cultural adjustment, and provide opportunities for international students to establish a sense of community at Caltech. Prior to the fall term, ISP hosts International Student Orientation to provide an introduction to academic and social life at Caltech and in the United States. All incoming international students are required to participate. Please contact ISP at isp@caltech.edu for more information on current programs, or visit ISP online at www.international.caltech.edu.

AUDITING COURSES

Persons not regularly enrolled in the Institute may audit courses if they obtain the consent of the instructor in charge of the course, and the dean of undergraduate students or dean of graduate studies, as appropriate, and pay the required fee (contact the Bursar's Office for audit fee). The fees are nonrefundable.

Auditing cards may be obtained in the Registrar's Office.

Regularly enrolled students and members of the faculty are not charged for auditing. Auditing cards are not required, but the instructor's consent is necessary in all cases. No grades for auditors are reported to the Registrar's Office, and no official record is kept of the work done.

GRADES AND GRADING

All permanent grades recorded for freshmen during the first and second terms they are enrolled will be either P, indicating "passed," or F, indicating "failed." The temporary grade of I ("incomplete") may be used as it is for other students. The temporary grade of E may be given to freshmen as described below for other students. It may also be used in a continuing course if the performance of the freshman concerned is not significantly below the current passing level, and if the student is maintaining a steady and substantial improvement; an E given for this reason will be automatically changed to a P if the freshman earns a P for the following term, and will change to an F if the student receives an F for the following term. The grade may not be used in this way for two successive terms nor for the last term of the course.

If a first-quarter or second-quarter freshman is enrolled in a course in which the instructor gives letter grades, the registrar will record P for all passing grades. No grades given to a freshman during the first and second quarter in which they are enrolled will be used in computing the cumulative grade-point average.

For all students beyond the first and second quarters of their freshman year, graduate and undergraduate, letter grades will ordinarily be used to indicate the character of the student's work: A, excellent; B, good; C, satisfactory; D, poor; E, conditional; F, failed; I, incomplete. P may also be used as described below under *Pass/Fail Grading*. In addition, grades of A+ and A–, B+ and B–, C+ and C–, and D+ may be used. In any situation in which no grade is reported, the grade shall be assumed to be F.

At their discretion, instructors may give students who have not completed their work for a course by the end of the term a grade of E. The grade E indicates deficiencies that may be made up without repeating the course. If the instructor does not specify a date on the grade report sheet for completion of the work, students receiving an E will have until Add Day of the following term to complete their work for that course. Instructors may, however, require the work for the course to be completed by an earlier date. If a student receives an E and does not complete the work by the date specified by the instructor or by Add Day, the grade will be changed to an F. Adequate time must be afforded to instructors to grade the work and to submit the final grade to the registrar.

It is the responsibility of a student receiving an E to confirm that the registrar has recorded the terms for satisfying the completion of the work in the course.

With the written permission of the instructor, a student may extend the E grade past Add Day of the following term, but doing so will cause an additional E grade to be registered. Each additional extension of the E will be until the date specified by the instructor or until Add Day of the following term, but in each case will require the written permission of the instructor and the registering of an additional E grade.

After an undergraduate student has been awarded the grade of E six times, he or she is not eligible to receive E grades in any subsequent term. A petition for an E in a subsequent term may be approved by the Undergraduate Academic Standards and Honors (UASH) Committee in an exceptional case. Such a petition requires the support of the instructor and the dean or associate dean of undergraduate students.

The grade I is given only in case of sickness or other emergency that justifies noncompletion of the work at the usual time. It is given at the discretion of the instructor, after approval by the dean or associate dean of students or the dean of graduate studies. The time period within which the grade of I is to be made up should be indicated on the grade sheet, or students receiving an I will have until Add Day of the following term to complete their work for the course. As in the case of the E grade, the grade of I shall not be considered in calculating a student's grade-point average.

Students receiving grades of E or I should consult with their instructors not later than the beginning of the next term in residence as to the work required and the time allowed. This time should, in most cases, coincide with the date fixed in the calendar for removal of conditions and incompletes (Add Day), and in fact if no other time is specified, this date will be assumed. However, except under extraordinary circumstances, the time for the completion of the work will not be extended beyond one year after the date in which the grade of E or I was given. An E will turn into an F one year after the date on which the E was given, and an I grade will turn into a W (standing for "withdrawn") one year after the date on which the I grade was given. That circumstances are so extraordinary that it allows waiving of this one year rule requires the agreement before that one year anniversary of the Dean of Undergraduate Students, Chair of UASH, and Executive Officer of the department in which the course was taken. Grades of E and I shall not be considered in calculating a student's grade-point average.

Failed means that no credit will be recorded for the course. The units, however, count in computing the student's grade-point average, unless the course was taken on a pass/fail basis. He or she may register to repeat the subject in a subsequent term and receive credit without regard to the previous grade, the new grade and units being counted as for any other course, but the original F and units for the course remain on the record. An F, once recorded, will be changed to a passing grade only on the basis of error. Such a change may be made only with the approval of the Undergraduate Academic Standards and Honors Committee or of the Graduate Studies Committee, whichever has jurisdiction.

Petitions by undergraduate students for late drops (i.e., requests to drop a course after Drop Day) will be considered by the UASH Committee. If approved, a W will be recorded on the student's transcript in place of a grade for that course. W's will not be included in the computation of the student's grade-point average. Courses will be expunged from the student's record only in exceptional circumstances, at the discretion of the UASH Committee.

Each course at the Institute is assigned a number of *units* corresponding to the total number of hours per week devoted to that subject, including classwork, laboratory, and the normal outside preparation. Credits are awarded as shown in the table below.

Grade-Point Average: Grade-point average is computed by dividing the total number of credits earned in a term or an academic year by the total number of units taken in the corresponding period. Units for which a grade of F has been received are counted, even though the course may have subsequently been repeated. Grades of P or F obtained in courses graded on a pass/fail basis are not included in computing grade-point average.

No. of Units	A+	A	A–	B+	B	B–	C+	C	C–	D+	D	F
1	4	4	4	3	3	3	2	2	2	1	1	0
2	9	8	7	7	6	5	5	4	3	3	2	0
3	13	12	11	10	9	8	7	6	5	4	3	0
4	17	16	15	13	12	11	9	8	7	5	4	0
5	22	20	18	17	15	13	12	10	8	7	5	0
6	26	24	22	20	18	16	14	12	10	8	6	0
7	30	28	26	23	21	19	16	14	12	9	7	0
8	35	32	29	27	24	21	19	16	13	11	8	0
9	39	36	33	30	27	24	21	18	15	12	9	0
10	43	40	37	33	30	27	23	20	17	13	10	0
11	48	44	40	37	33	29	26	22	18	15	11	0
12	52	48	44	40	36	32	28	24	20	16	12	0
13	56	52	48	43	39	35	30	26	22	17	13	0
14	61	56	51	47	42	37	33	28	23	19	14	0
15	65	60	55	50	45	40	35	30	25	20	15	0

Pass/Fail Grading: The following regulations apply:

- First-quarter and second-quarter freshmen receive pass/fail grades in all courses by virtue of their classification as freshmenby an admissions committee or, for students whose status after the first year is uncertain, by the Undergraduate AcademicStandards and Honors Committee.
- All other students, undergraduate and graduate, in courses with numbers under 200 will receive letter grades unless the course is designated "graded pass/fail" or unless, when it is allowed, the student files with the Registrar's Office a completed Pass/Fail Course Selection Card not later than the last day for dropping courses.
- In courses with numbers 200 or greater that are not designated either "graded pass/fail" or "letter grades only," the instructor may decide separately for each student what class of grades to use.
- All research courses shall be designated "graded pass/fail." All reading courses, seminar courses, or other courses that do not have a formal class structure shall be designated "graded pass/fail" unless the option secures an exemption from the Curriculum Committee or the Graduate Studies Committee and from the Faculty Board.
- A grade on the pass/fail system should be P if it would have been a D or better on the letter grade system. (Note that there is no D– grade.) The standards of failure in courses in which only pass/fail grades are used should be the same as they would be if the course were letter graded.
- Any instructor may, at his or her discretion, specify prior to

registration that his or her course, if not classified by the above regulations, is to be graded on a "letter grades only" basis or is to be graded pass/fail only, subject to possible review by the responsible option. The registrar must be notified of such specification two weeks before the beginning of registration. (Note: If the grading scheme is changed during the term, it is changed for everyone.)

- Each term, any student may select, subject to such requirements as may be imposed by the student's option, two elective courses in which he or she is to be graded on a pass/fail basis if it is not designated as "letter grades only" and is not specifically required for the degree in his or her option. To make this election, a completed Pass/Fail Course Selection Card must be submitted to the Registrar's Office on or before the last day for dropping courses that term. This election may be reversed or reinstated at any time before the deadline. The election must be approved and the card signed by the student's adviser. The instructor must be notified and should sign the card to indicate that this has been done; the instructor must allow any eligible student to make this election.
- Of the units offered to satisfy the requirements for the Bachelor of Science degree, no more than 90 may be in courses graded pass/fail because of the student's election.

Procedures for Resolving Disputes over Grading

At Caltech, the instructor has full responsibility for assigning grades to students enrolled in a course. On occasion, a student may not understand how a grade was determined and may seek further information. The student should first meet with the instructor or teaching assistant to discuss the grade. If after doing so the student believes the grade is unjustified or capricious, the following procedures are available.

Before the end of the term following the term when the grade was issued, the student should contact the academic mediator, appointed by the provost, who will work with the student and instructor to resolve the problem. If the mediation effort is unsatisfactory to the student, he or she may request a formal review by an appropriate executive officer or academic officer. The executive officer will review the case and report the decision in writing to the student. If the executive officer decides that a change of grade is warranted, or if the student requests a further appeal, these shall be requested of the division chair. At the discretion of the division chair, a committee may be appointed to review the case. The committee members should interview everyone involved in the case (the student, the course instructor, the teaching assistant, and anyone else with relevant information), and make a written recommendation to the division chair. Only the division chair can authorize the registrar to enter a new grade in the student's transcript.

NOTICES AND AGREEMENTS

Academic Records of Veterans

The Institute maintains a written record of a student's previous education. This is part of the student's official transcript, and included on this is a summary of any prior college-level education. A true copy of a transcript of college-level work at other institutions is maintained as part of the student's record. The amount of credit granted for prior training is indicated on the student's official transcript and, where this results in the shortening of a required training period in the case of a veteran, the Veterans Administration is notified.

The Institute's official transcript for each student shows the progress that student is making at the Institute. There is a record of each course enrolled in each term with a grade recorded for the course. The total number of units earned is kept so that the record will show continued progress toward the degree sought. The final grades are recorded at the end of each term of the school year, and the accumulative permanent record has on it grades for all subjects taken at the Institute. No student is allowed to enroll repeatedly in a course and withdraw without penalty. If a student enrolls in a course, he or she is expected to complete the course or receive a failing grade unless he or she withdraws from the course prior to the deadline for dropping courses. All students must maintain a minimum load equivalent to 12 quarter hours each term; no student may drop courses that would bring him or her below this level of effort. At any time when the student falls below the required number of units, fails to receive satisfactory grades, or engages in unsatisfactory conduct, the record is marked to indicate this, and the student is forbidden to continue at the Institute.

The grading system of the Institute is A+ (excellent) to F (failed). An A+ is equivalent to 4.3 and an F to 0.0. A student must maintain a grade-point average of 1.9 in any term in order to be able to enroll in a successive term at the Institute. A minimum 1.9 overall grade-point average is required for graduation. A student who drops below the required average (1.9 for a given term) is dismissed and must petition for reinstatement. A student may be reinstated by the Undergraduate Academic Standards and Honors Committee and, if so, is required to earn a 1.9 GPA during the immediately following term. The Veterans Administration is notified when a veteran is academically dismissed or is making unsatisfactory progress toward a degree. Since the Institute requires all students to carry a minimum full load that corresponds to 12 quarter hours each term, any student who finishes a term in good standing is considered to have made satisfactory progress. If a student withdraws from a course before the final date for withdrawal, no grade is given in that course. The time spent in school counts, however, and the student may be considered to have not made satisfactory progress in the event of such withdrawal.

In order to withdraw from any course, a student must submit a withdrawal card. This shows the date on which the student was last in official attendance in that course. If a student reenrolls in that course and successfully completes it, that fact will be noted on his or her official transcript.

Access to Student Records

The Institute maintains educational records for each student that include name, address, student identification number (including Social Security number), information on parents, guardian, and spouse, general information on academic status at the Institute, previous school data, results of standardized admissions examinations, courses previously taken or being taken, credits, and grades. Applicants for financial aid have an additional file holding those records. The Family Education Rights and Privacy Act (FERPA) and Caltech policy afford students certain rights as well as establish limitations with respect to student educational records. These rights and limitations are as follows:

1. The registrar of the Institute is responsible for maintaining all educational records, except for those involving financial aid. Caltech permits disclosure of educational records, without consent of the student, to Institute officials with legitimate educational interests in them. An Institute official is a person employed by the Institute in an administrative, supervisory, academic or research, or support-staff position (including security personnel and health and diversity center staff), a person or company with whom the Institute has contracted (such as an attorney, auditor, consultants, contractors, or collection agent), a person serving on the Board of Trustees, or a student serving on an official committee, such as a disciplinary or grievance committee, or assisting another Institute official in performing his or her tasks. An Institute official has a legitimate educational interest if he or she needs to review an educational record in order to fulfill his or her professional responsibility. They are available to the registrar, provost, president, general counsel, vice president for development and institute relations, vice president for student affairs, dean of graduate studies, dean of undergraduate students, director of financial aid, and faculty of the Institute and their respective staffs for the normal academic and business purposes of the Institute. Records involving financial aid are maintained by the director of financial aid, and are available to the director and staff, to the dean of graduate studies and staff, to the Faculty Committee on Scholarships and Financial Aid, and to the Faculty Committee on Graduate Study, for the purpose of granting and administering the Institute's financial aid program. Except as authorized by federal or state law or regulation, none of these educational records nor any personally identifiable information contained therein, other than directory information (see below), will be made available to anyone else, other than the student, without the written consent of that student. Where consent is required and given, the student, upon request, will receive a copy of the

records to be released. The Institute will keep a record, available to the student and kept with his or her file, of all persons and organizations, other than those authorized within the Institute, requesting or obtaining access to the files. The exception is when records have been produced in response to a grand-jury subpoena or other subpoena issued for a law-enforcement purpose and the court or issuing agency has ordered that the existence or the contents of the subpoena or the information furnished in response to the subpoena not be disclosed.

2. Students are allowed access to their educational records as follows: A student may inspect his or her academic transcript during normal working hours. To see other records, the student must provide a written request to the registrar or to the director of financial aid or to the dean of graduate studies or to the dean of undergraduate students, or their deputies, as appropriate. A mutually convenient time will be arranged within 10 working days after receipt of the request for the student to examine the records in his or her file. At that time the student may examine all educational records in the file with the exception of those specifically exempted by Part 99 of Title 34 of the Code of Federal Regulations. The student may obtain copies of any of the records available to him or her; the cost will be $10 plus 25 cents per page. If a student believes the educational records relating to the student contain information that is inaccurate, misleading, or in violation of the student's rights of privacy, the student may ask the Institute to amend the record. The Institute will decide whether to amend the records as requested within a reasonable time after receiving the request. If the registrar, or the director of financial aid, or the dean of graduate studies, or the dean of undergraduate students, or their deputies, do not agree to amend any item contained or not contained in the educational records, the student will be informed of the decision and of his or her right to a hearing. The student may submit a written request to the vice president for student affairs or his/her designee for a hearing to challenge the content of the records on the grounds that the information contained in the records is inaccurate, misleading or in violation of the privacy rights of the student. The vice president for student affairs or his/her designee will schedule such a hearing within a reasonable time after receipt of the request and will notify the student at a time reasonably in advance of the hearing of its date, time, and place. The student will be afforded a full and fair opportunity to present evidence relevant to the issues raised and may be assisted or represented by individuals of his or her choice at his or her own expense, including an attorney. The decision of the vice president or designee will be in writing, will be rendered within a reasonable time after the conclusion of the hearing, and will be final. This decision will be based solely upon the evidence presented at the hearing and will include a summary of

the evidence and of the reasons for the decision. If, as a result of the hearing, the Institute decides that the information is inaccurate, misleading, or otherwise in violation of the privacy rights of the student, the Institute shall amend the records accordingly, and so inform the student in writing. However, if, as a result of the hearing, the Institute decides that the information is not inaccurate, misleading, or otherwise in violation of the privacy rights of a student, it shall inform the student of the right to place in the educational records a statement commenting on the information in the records and/or setting forth any reasons for disagreeing with the decision of the Institute.

3. The Institute considers the following to be directory information: a student's name, UID, addresses (permanent, campus and local/off-campus, and e-mail), associated telephone listings, ID photograph, date and place of birth, major field of study, year in school, current enrollment status, expected date of graduation, name of academic adviser, participation in officially recognized activities and sports, weight and height if a member of an athletic team, dates of attendance, degrees and awards received, thesis title, hometown, and most recently attended educational agency or institution. Directory information may be made available to requestors at the Institute's discretion. Any student may, however, have part or all of this information withheld by notifying the registrar in writing no later than 30 days after the commencement of classes in the academic year. That information will then be withheld for the balance of that academic year. If the information is to be withheld in subsequent years, new requests must be filed.
4. A student will not be required to waive any rights regarding access to educational records. However, a student may voluntarily waive right of access to confidential statements made by third parties respecting admission to educational agencies or institutions, applications for employment, or the receipt of an honor or honorary recognition. In case of waiver, the confidential statements will be used solely for the purposes for which they were specifically intended, and the student will, upon request, be notified of the names of all persons making such confidential statements. If a student should desire to waive right of access, so as to facilitate the obtaining of a confidential statement of this nature, he or she should contact the registrar for the necessary form.
5. The Institute reserves the right to destroy from time to time any and all educational records that it maintains on a student, except to the extent that the law requires their maintenance for a longer period of time. However, where access to records has been requested, no destruction of those records will be allowed to take place until such access has been granted or denied.
6. Students who believe their rights under FERPA may have been violated may file a complaint with the Family Policy

Compliance Office, U.S. Department of Education, 400 Maryland Avenue SW, Washington D.C. 20202-4605.

Transcripts of Records
A student, or former student, may request that official transcripts of his or her records be forwarded to designated institutions or individuals. Requests should be filed at the Registrar's Office at least five days before the date on which the transcripts are to be mailed.

Accreditations and Authorizations

The California Institute of Technology is accredited by the Accrediting Commission for Senior Colleges and Universities of the Western Association of Schools and Colleges, 985 Atlantic Ave., Ste. 100, Alameda, CA 94501; (510) 748-9001. In addition, the Institute is authorized by the California State Department of Education, Office of Private Postsecondary Education, to operate as a private postsecondary educational institution and, by the same agency, to train veterans in the programs of the Veterans Administration.

The Engineering Accreditation Commission of ABET, Inc. (111 Market Place, Suite 1050, Baltimore, MD 21202-4012; 410-347-7700), has accredited Caltech's B.S. programs in chemical engineering, in electrical engineering, and in mechanical engineering. Further, the Committee on Professional Training of the American Chemical Society has approved Caltech's B.S. program in chemistry.

The documents describing these accreditations and authorizations are on file and may be inspected in the Registrar's Office and the Provost's Office; the office of the Division of Engineering and Applied Science also has the documentation for ABET.

Student Problem Resolution Process

Caltech provides a variety of routes, most of them informal, by which students may bring complaints for consideration and resolution. For example, in academic matters, students may begin with faculty-student conversations that may extend to the deans, the option representatives, the division chairs, the registrar, or to various committees having faculty and student members. Non-academic matters can be dealt with informally by student leaders, resident associates, the residence life coordinators, the deans, and other student affairs offices. The Graduate Student Council (GSC) and the Associated Students of the California Institute of Technology (ASCIT) may become involved in some complaints, and sometimes ad hoc groups are formed to make recommendations.

The Problem-Resolution Process (Process) is intended to deal with complaints by currently enrolled students for which reasonable efforts by the available informal routes have not lead to an acceptable resolution and which do not fall within the jurisdiction of other Policies or the Honor System.

The first step in this Process is for the student to consult with the appropriate deans. One of the deans will then determine if this issue falls under this Process and, if appropriate, will appoint a mediator to help resolve the issue. If the student's issue involves a decision or action of a dean, the vice president of student affairs will appoint a mediator to help resolve the issue.

The mediator will assist the student in trying to work out the problem. If the student is not satisfied with the results, the student may file a written notice of appeal to the vice president for student affairs. The decision of the vice president is final.

If the student has a complaint about Caltech's compliance with academic program quality and accrediting standards that they believe warrants further attention after exhausting the steps outlined above, they may contact the Western Association of Schools and Colleges (WASC) at http://www.wascsenior.org/comments. WASC is the academic accrediting body for Caltech. An individual may contact the Bureau for Private Postsecondary Education for review of a compliant. The bureau may be contacted at 2535 Capitol Oaks Drive, Suite 400, Sacramento, CA 95833, website: www.bppe.ca.gov, telephone: (916) 431-6924; fax: (916) 263-1897. Prospective students may contact WASC or the BPPE with complaints as well.

Student Patent and Computer Software Agreement

The California Institute of Technology (Caltech) has a responsibility to see that inventions and copyrightable materials (including software) developed in connection with Caltech be used for the public benefit, and be consistent with Caltech's contractual obligations. In view of the patent and copyright policies of Caltech in force on this date and as may from time to time be amended, and my use of and access to Caltech facilities and equipment, I agree to the following:

Caltech retains all rights in inventions and computer software I generate as a student at the Caltech campus, Jet Propulsion Laboratory (JPL), and other facilities owned or managed by Caltech, with the following exceptions:

1. When I generate copyrightable computer software or other written work at Caltech in connection with my enrollment in Caltech's educational program, such as in course work, homework, theses and publications, I understand that I will retain ownership of copyrights to these works, and I hereby grant to Caltech an irrevocable royalty-free nonexclusive license to use such computer software and written work for educational and research purposes, including the right to grant sublicenses. If the work is generated at JPL or any Caltech owned or managed facility, I also hereby grant to the United States Government ("Government") a royaltyfree, nonexclusive license to use such computer software and written work for purposes for or on behalf of th2 Government, to the extent Caltech or the Government requires such a license.
2. When I make inventions, write computer software or other written work entirely on my own time, without using Caltech's equipment or facilities (other than incidental use of electronic

information resources as is permitted under Caltech policy), and without using Caltech funds, I retain ownership of those inventions, software and written work.

I agree to assign, and hereby do assign, to Caltech all inventions and copyrightable materials that I develop with the use of funds administered by Caltech, or in the course of my duties at or for Caltech, including JPL, or with use of other facilities owned or managed by Caltech, apart from those for which I retain rights under numbered paragraphs 1 and 2 of this agreement, and all copyrights, patent applications and patents relating to those inventions and copyrightable materials.

I agree to execute all papers required to apply for, obtain, maintain, issue and enforce the assigned copyright registrations, patents and applications; and to provide reasonable assistance regarding those copyrights, patents and patent applications, including testifying in any related patent office proceeding, dispute or litigation. Expenses for the copyrights and patent applications, and for the assistance set forth in the preceding sentence, shall be borne entirely by Caltech.

I agree to notify Caltech promptly of all such assigned inventions or copyrightable materials.

I understand that if Caltech receives funds from the licensing of the assigned copyrightable materials or patents in excess of unreimbursed expenses associated with obtaining, maintaining and enforcing those copyrights and patents, I will share in these funds according to the established Caltech policy, procedures and practice in effect on the date that the patent application is filed or the computer software is completed, in the same manner as a member of the academic staff and employees.

I agree to notify Caltech of any funding of which I am aware that may have supported an assigned invention described in the preceding paragraphs. This is to ensure Caltech's compliance with its obligations, including the provisions of the Federal Bayh-Dole Act and implementing regulations. For work done at JPL, I agree to have all scientific and technical publications reviewed, pursuant to JPL policy, prior to public release to ensure compliance with U.S. export control laws.

I understand that Caltech relies on this agreement when it enters into contracts with others and obligates itself with respect to inventions and computer software developed at Caltech.

Revised 03-23-2015

Student Retention and Persistence Rates

Most undergraduates enter Caltech at the freshman level. Of the 248 freshmen enrolled during the 2013–14 academic year, 240 reenrolled in the first term of the 2014–15 academic year and are progressing, yielding a persistence rate of 97 percent after all allowable exclusions. Of the 236 freshmen enrolled during the 2008–09 academic year, 216 graduated by June 2014, yielding a graduation rate for this group of 92 percent after allowable exclusions.

At the graduate level, most students enter Caltech to pursue either the degree of Master of Science or Doctor of Philosophy or, occasionally, both. Of the 219 entering graduate students enrolled in a Ph.D. program during the 2013–14 academic year, 209 reenrolled in the first term of the 2014–15 academic year and are making satisfactory academic progress, resulting in a persistence rate of 95 percent. Of the 19 entering graduate students enrolled in M.S. programs during the 2013–14 academic year, 11 earned a terminal M.S. degree within one year.

Undergraduate Student Events

Caltech is committed to providing its students, faculty and staff with an environment that promotes safe and responsible social interaction. Caltech recognizes that student parties and activities are an important part of campus life. Students are required to follow Event Planning Procedures set forth on the Deans Office website: http://deans.caltech.edu/Services/PartyPlan

INSTITUTE POLICIES

Acceptable Use of Electronic Information Resources

Caltech provides electronic information resources (including, but not limited to, computers, computer accounts and services, networks, software, electronic mail services, electronic information sources, video and voice services, servers, web pages, and related services) to assist members of the Institute community in the pursuit of education and research. This policy, in conjunction with other applicable

Caltech policies, sets forth the acceptable use of all electronic information resources owned or managed by Caltech, and describes the rights and responsibilities of the Institute and of faculty, staff, students, and other members of the Institute community with respect to the use of these resources.

Electronic information resources provided by Caltech are intended to be used to carry out the legitimate business of the Institute, although some incidental personal use is permitted. Faculty, staff, students, and other members of the Institute community ("users") who use Caltech's electronic information resources should be guided by the Honor Code, which prohibits any member of the Institute community from taking unfair advantage of any other member of the Caltech community, and the Code of Conduct. Users assume responsibility for the appropriate use of the Institute's electronic information resources and agree to comply with all relevant Institute policies and all applicable local, state, and federal laws. Examples of inappropriate or unauthorized use of the Institute's electronic information resources include:

- sending a communication or using electronic information resources, including web pages, that
- Illegally discriminate against, harass, defame, or threaten individuals or organizations;
- engaging in illegal conduct or conduct that violates Institute policy;

• destruction of or damage to equipment, software, or data belonging to others;
• disruption or unauthorized monitoring of electronic communications;
• interference with use of Institute systems;
• violations of computer security systems;
• unauthorized use of accounts, access codes, or identification numbers;
• use that intentionally impedes the legitimate computing activities of others;
• use for commercial purposes;
• use for political or lobbying activities that jeopardize the Institute's tax exempt status and, therefore, violate Institute policy;
• violation of copyrights, software license agreements, patent protections and authorizations, or protections on proprietary or confidential information;
• unauthorized use of Caltech's trademarks;
• violating copyright laws by downloading and sharing files;
• violations of privacy;
• academic dishonesty;
• sending chain mail;
• spamming;
• downloading, viewing, and/or sharing of materials in violation of the Institute's policy regarding Unlawful Harassment, including Sexual Violence (http://www.hr.caltech.edu/services/policies);
• intrusion into computer systems to alter or destroy data or computer programs (e.g., hacking or cracking); or
• sending communications that attempt to hide the identity of the sender or represent the sender as someone else.

This policy will not be construed or applied in a manner that improperly interferes with employees' rights under the National Labor Relations Act.

Caltech's electronic information resources are Institute property and users should not have an expectation of privacy with respect to their use of these resources or the data, files, or other records generated, stored, or maintained on them. Password capabilities and other safeguards are provided to users in order to safeguard electronic messages, data, files, and other records (including computer files and records, electronic mail, and voice mail) from unauthorized use. These safeguards are not intended to provide confidentiality from the Institute with respect to personal messages or files stored on electronic information resources owned and managed by Caltech.

In order to protect the integrity of its electronic information resources, the Institute routinely examines network transmission patterns such as source/destination, address/port, flags, packet size, packet rate, and other indicators of traffic on its servers. The Institute will follow up on any system and/or account that appears to be compromised or is in the process of being compromised. Caltech typically does not review the content of electronic messages or other data, files, or records generated, stored, or maintained on its electronic information resources; however, it retains the right to inspect, review, or retain the content of such messages, data, files, and records at any time without prior notification. Any such action will be taken for reasons the Institute, within its discretion, deems to be legitimate. These legitimate reasons may include, but are not limited to, responding to lawful subpoenas or court orders; investigating misconduct (including research misconduct); determining compliance with Institute policies and the law; and locating electronic messages, data, files, or other records related to these purposes. Users must therefore understand that electronic messages, data, files, and other records generated, stored, or maintained on Institute electronic information resources may be electronically accessed, reconstructed, or retrieved by the Institute even after they have been deleted.

Institute access to the content of electronic mail, data, files, or other records generated, stored, or maintained by any user for reasons such as those described in the previous paragraph must be authorized as follows: (1) by the Provost for any situations that require access to electronic materials associated with faculty; (2) by the Vice President for Business and Finance for staff at campus or the JPL Director for Human Resources for staff at JPL; (3) by the Vice President for Student Affairs for students; or (4) by the General Counsel for the purposes of complying with legal process and requirements or to preserve user electronic information for possible subsequent access in accordance with this policy. In all cases, the Office of the General Counsel should be consulted prior to making a decision on whether to grant access. In the case of a time-critical matter, if the authorizing official cannot be located, the General Counsel may authorize access.

The Office of General Counsel will work with Information Management Systems and Services to prepare an annual summary report of all activity authorized under this policy. The report shall be provided to both the President and the Provost.

In conclusion, the use of Institute electronic information resources is a privilege, not a right, and the Institute may revoke this privilege or decline to extend this privilege at any time. Inappropriate use of Institute resources may result in administrative discipline up to and including separation from the Institute. Suspected illegal acts involving Institute electronic information resources may be reported to state and/or federal authorities, and may result in prosecution by those authorities. Any questions concerning the appropriate use of any of the Institute's electronic information resources or relevant

Institute policies should be directed to the provost, the general counsel, the chief information officer, the associate vice president for human resources, the dean of undergraduate students, or the dean of graduate studies.

Compliance with Export Laws & Regulations

The mission of the California Institute of Technology is to expand human knowledge and benefit society through research integrated with education. We investigate the most challenging, fundamental problems in science and technology in a singularly collegial, interdisciplinary atmosphere, while educating outstanding students to become creative members of society.

Export control laws and regulations as referred to in this Policy include a number of federal laws and regulations that impact an export or import transaction such as those of the Departments of State, Commerce, Treasury, Defense, Energy and U.S. Customs. These laws have existed for many years, however, the events of September 11, 2001 and subsequent events around the world have pushed national security concerns to the forefront. The U.S. government has responded to global security concerns by tightening the export control regulations that govern the transfer of U.S. strategic technology for national security and foreign policy reasons and in furtherance of economic objectives.

The export control laws are intended to control the transfer of sensitive information or goods to individuals, entities or countries of concern and, under certain conditions, to foreign persons. The regulations contain a fundamental research exclusion and specific university exemptions that allow most of the research activities being performed at U.S. colleges and universities to be carried out without the need of export licenses or other restrictions, subject to certain conditions.

Caltech is an institution of higher learning conducting fundamental research in science and engineering. The fundamental research exclusion, however, does not fully relieve us of our responsibility to comply with the export control regulations.

The fundamental research exclusion, as defined in the U.S. export regulations, applies to basic and applied research in science and engineering performed by colleges and universities, so long as that research is carried out openly and without restrictions on publication or access to or dissemination of the research results.

The presidential National Security Decision Directive 189 (NSDD 189) recognizes the important contributions that U.S. universities make in science and engineering that allow our nation to remain innovative and competitive. NSDD 189 provides the framework for the fundamental research exclusion.

The fundamental research exclusion applies only to research conducted in the United States. This exclusion allows most of the activities conducted at Caltech to be performed without the need of an export license. However, there are certain activities and information that are not covered by the fundamental research exclusion and remain subject to the export control laws and regulations.

Examples of these are:

1. Receipt by the Institute of third-party export controlled information which requires that appropriate measures be taken to ensure that the information is properly safeguarded. Under

certain conditions, the disclosure of specific information and the provision of specific types of services to foreign persons (non U.S. citizens, non-legal permanent residents, or non-U.S. legal entities) inside the United States ("deemed exports");
2. Travel abroad: Engaging in specific activities with persons and entities abroad, even if the information relied upon is publicly available;
3. The export of controlled items and information outside the United States including: controlled hardware, software and technology; and
4. Financial transactions or other dealings involving prohibited parties or sanctioned countries.

The export control laws and regulations may apply to research activities whether or not they are funded by grants or contracts.

Caltech takes its freedom to publish and its commitment to openness in research very seriously. Caltech's policy, as set forth in the Faculty Handbook, does not allow acceptance of any government contract or grant that requires classified research to be carried out on campus or which impinges upon the Institute's freedom to publish and otherwise disseminate the results of its research. For that reason, Caltech undergraduate students shall not be given certain export-controlled technology, i.e., ITAR-controlled technical data, software, and items, if such access would jeopardize their ability to publish.

The export control laws are administered by the U.S. Department of Commerce through its Export Administration Regulations (EAR – dual-use items), the U.S. Department of State through its International Traffic in Arms Regulations (ITAR – space and military items), and the U.S. Department of Treasury through its Office of Foreign Assets Control (OFAC – economic and trade sanctions). These laws control the conditions under which certain information, technologies, and commodities can be transmitted overseas to anyone, including U.S. citizens, or to a foreign person on U.S. soil. Caltech is committed to comply fully with these federal laws and regulations.

To that end, Caltech has established an Export Compliance Office and has appointed a Director for Export Compliance who also functions as Caltech's Empowered Official. The Empowered Official is the person who has legal authority to sign export control license applications and other requests for export approval on behalf of Caltech, and is the person responsible for developing and implementing export compliance programs, campus procedures, awareness programs for faculty and training programs for staff.

Caltech expects all faculty and staff to comply fully with all applicable export control laws and regulations. Noncompliance may result in violations that can subject both the individual and the Institute to civil sanctions and criminal penalties.

It is the responsibility of Caltech faculty and staff to ensure the Institute's compliance with this policy.

The following individuals have been designated as contacts regarding export control issues:

Adilia F. Koch, Director for Export Compliance, (626) 395-4469 or the Export Office staff at (626) 395-2641 or export@caltech.edu.

Conflicts of Interest Policy

The mission of the California Institute of Technology (Caltech) is to expand human knowledge and benefit society through research integrated with education. In pursuit of this mission, Caltech adheres to the Eleven Principles comprising its code of conduct and strives for the highest level of integrity and public confidence. Caltech's integrity rests on the personal integrity of each of us who is called upon to act on behalf of the Institute. Caltech is committed to ensuring that decisions made on its behalf reflect the highest ethical standards and that its research and instruction remain a rigorous and open inquiry, unencumbered by conflicts of interest, real or perceived, that might affect the sound judgment of the trustees, officers, senior management, faculty, students and staff. Each of us, therefore, is responsible for identifying and resolving conflicts between personal and Institutional interests. We each must act in the best interests of the Institute and refrain from taking part in any transaction where we do not believe in good faith that we can act impartially.

Individual conflicts of interest may affect the Institute's trustees, officers, faculty, or staff. An individual conflict of interest is a situation that may compromise an individual's professional judgment in carrying out Institute business due to an external relationship that directly or indirectly affects the interest of the individual or an immediate family member. Each situation that presents a potential for conflict of interest must be fully disclosed to the Institute, and managed or eliminated before moving forward. Conflicts of interest also include conflicts of commitment which are situations in which external activities, either paid or unpaid, interfere with an employee's primary obligation and commitment to the Institute.

In academic research, the term conflict of interest refers especially to situations in which financial or other personal considerations may compromise, or may have the appearance of compromising, an investigator's professional judgment in conducting or reporting research. The bias can affect collection, analysis, and interpretation of data, hiring of staff, and procurement of materials, sharing of results, choice of protocol, and the use of statistical methods. Conflicts of interest can affect all scholarly fields.

Caltech has established these conflict of interest policies and procedures that apply to all Caltech employees, including faculty, to ensure compliance with Caltech's ethical standards as well as with the laws, rules, and regulations that govern Institute activities, while fostering and sustaining an environment of openness and integrity.unlaw

Individual Conflicts of Interest

The broad principles in this policy encompass a variety of situations, many of which do not fall into patterns for which specific guidelines may be established. Conflicts of interest inevitably arise from time to time in everyday business life; some may appear to be inconsequential or may even be advantageous to the Institute. It is important, however, that all employees make timely disclosure of any such conflict of interest. Each employee should apply his or her sense of integrity and common sense to disclose any circumstances that are, may become, or may give the appearance of a possible conflict of interest. Supplementing this broad policy statement are the following rules to be observed on specific matters:

1. Each employee has a duty to act in the best interest of the Institute and avoid actions that would call into question the integrity of the employee or the Institute.
2. An employee who has directly or through family or business connections, a material interest in suppliers of goods or services, or an interest in contractors or potential contractors with the Institute, should not act on behalf of the Institute in any transaction involving that interest. No employee should participate in the selection, award, or administration of a contract with any party with whom he/she is negotiating regarding potential employment or any arrangement concerning potential employment.
3. An employee should avoid outside employment or business activity involving obligations which may conflict or appear to conflict with Institute interests, including its interest in the full- or part-time services of any staff member (i.e. a conflict of commitment). Outside employment, directorships, consulting or similar arrangements, other than with government entities, must be disclosed to the Division Chair for faculty, the staff member's supervisor and the Associate Vice President for Human Resources for campus staff and the JPL Ethics office and HR office for JPL staff. Campus and JPL staff are required to obtain approval prior to engaging in outside employment, consulting or other business activities. Campus staff must complete the Application for Outside Employment, Consulting or Business Activity form pursuant to Personnel Memorandum PM 9-3, JPL staff must complete the Request for Outside Activity form pursuant to JPL Rule 8718.
4. To avoid the appearance of a conflict of interest, an employee should provide full disclosure of any business or financial enterprise or activity in which he/she is involved which might influence, or might appear to influence, his/her official decisions or actions on Institute matters.
5. An employee should refrain from personal activities that include, but are not limited to, the purchase or sale of securities, real property, or other goods or services in which he/she could

use or might appear to have the opportunity to use, for personal gain, confidential information or special knowledge gained as a result of his/her relationship with the Institute.

6. An employee should refrain from unauthorized disclosure of non-public information concerning the Institute. Additionally, an employee should not use non-public information accessed through the performance of a government contract for personal gain.
7. No employee should make unauthorized use of Institute resources for his/her personal benefit or for the benefit of any other person. Incidental personal use of resources is authorized by the Institute. See Institute Policy on Acceptable Use of Electronic Information Resources and JPL Rules!
8. It is sound practice to discourage gifts and favors from people with whom the Institute has a business relationship. Personal gifts of more than nominal value should be tactfully declined or returned to avoid any appearance or suggestion of improper influence. Any employee involved in awarding or administering contracts using federal or other government funds should keep in mind that state and federal law contain prohibitions against soliciting or accepting gratuities, favors or anything of monetary value from contractors or potential contractors.
9. Any employee doing business on behalf of the Institute with specific vendors should refrain from participating on leisure trips with representatives of those vendors. Such trips are not appropriate, even when a staff employee pays a fee to the vendor to participate in such trips.
10. No employee should act in any Institute matter involving a member of his/her immediate family including, but not limited to, matters affecting family members' employment or evaluation or advancement in the Institute, without first making full disclosure to the Division Chair for faculty, the staff member's supervisor and the Associate Vice President for Human Resources for campus staff and the JPL Ethics office and HR office for JPL staff. Such disclosure should include the nature of the familial relationship and the impact or potential impact of the employee's action on such family member. Immediate family includes spouse or domestic partner and children.

Any employee who believes that his/her conduct or activities may or may appear to conflict with these guidelines or activities or otherwise create a conflict of interest, should make an appropriate disclosure. You may also report possible conflicts of interest by calling the Compliance Hotline at 626-395-8787 or submitting a compliance hotline form. JPL employees should consult Laboratory requirements, and seek guidance and/or report possible conflicts of interest by contacting the JPL Ethics Office.

Additional Faculty Responsibilities
It is acknowledged that, in their wider roles as academicians and professionals, the faculty may be subject to conflicts of interest that are not necessarily financial and that are not within the scope of a policy that is designed to address conflicts of interest in the employer-employee setting. For example, this policy is not designed to address conflicts that may be encountered in service to a professional society. Academic and professional activities not covered by this policy are best handled within the ethical guidelines established by the Faculty Handbook. Faculty members must be aware of potential conflicts to ensure an open and productive environment for research and teaching. Conflicts of interest may arise when faculty members have the opportunity to influence the Institute's business decisions or when outside relationships may or may appear to compromise the integrity of decisions made as teachers and researchers. A faculty member's general commitment to the Institute requires that the member perform his/her responsibilities to the Institute and appropriately use his/her own judgment in deciding whether to engage in a variety of extramural activities, within the confines set forth in the Faculty Handbook. As a result, the

Institute relies on its faculty to be alert to the possible effect of outside activities on the integrity of his/her decisions and on his/her ability to fulfill his/her obligations to the Institute. Accordingly, in addition to the conflict rules set forth above, the following guidance is provided for faculty:

1. Some activities and interests are unlikely to lead to serious conflicts of interest and do not require disclosure. An example is a faculty member's entitlement to royalties or honoraria for published scholarly works and other writings or occasional lectures. Likewise, no serious conflicts arise when a faculty members serves as a consultant to a government agency, receives royalties under Institute royalty-sharing policies or owns equity in a business solely for the faculty member's consulting activities.
2. Disclosure to the Division Chair is mandatory if the faculty member directs students into a research area and, as a result, the faculty member intends to realize financial gain. An example is a research area within the ambit of a business in which the faculty member has a significant ownership interest or which employs the faculty member as a consultant. Any involvement of undergraduates, graduate students or post-doctoral scholars in the outside professional activities of the faculty member directing the student's research must be specifically approved in advance by the Division Chair. The student must also sign the written disclosure to signify understanding of the issues involved.
3. Disclosure to the Division Chair is mandatory if the faculty member has a significant interest in a business under circumstances that link the fortunes of the business to the faculty member's research.

4. Disclosure to the Division Chair is required if the faculty member is to receive sponsored support for research from a business for which the faculty member is a consultant, or in which the faculty member has a significant financial interest.

Conflict of Interest Requirements Imposed by Federal Sponsors
The National Science Foundation (NSF) and Public Health Services (PHS) have issued specific rules regarding the disclosure of significant financial interests and the management of financial conflicts of interest as a condition for submitting proposals and accepting awards of financial support from these agencies. Members of the Caltech Community proposing or working on any activity funded by NSF or PHS (including the National Institutes of Health) are required to comply with Caltech's Policy and Procedures for Managing Conflict of Interest Requirements Imposed by Federal Sponsors.

Institutional Conflicts of Interest Policy
Institutional conflicts of interest differ from individual conflicts of interest. An institutional conflict of interest is a situation in which the research, teaching, outreach, or other activities of the Institute may be compromised because of an external financial or business relationship held by the Institute that may bring financial gain to the Institute.

Institutional Conflicts of Interest
The Institute has many legitimate interests that may at times conflict. Management of institutional conflicts of interest is by its very nature more complex than that of individual conflicts of interest. External relationships to sponsors and supporters of the institution, the local community's acceptance of economic development activities, the institution's obligations as a charitable organization receiving preferential tax treatment, and the institution's perception of its teaching, research, and academic missions all impact how potential conflicts of interest are managed. The examples and issues presented below do not necessarily constitute inappropriate conflicts of interest. Each situation must be judged on the facts and merits of the relationship with an eye to what reasonable individuals outside the Institute might consider to be appropriate. Any activity, financial and/or operational, that may bring into question the Institute's reputation, integrity, and objectivity should be considered for possible conflicts of interest. The following are examples of potential situations that may give rise to institutional conflicts of interest:

1. Significant gifts to the Institute from a commercial sponsor of research may raise questions about the influence of the company on Caltech's research programs and how they are managed. Similar concerns arise when individual companies sponsor research or provide significant consulting income to a significant number of faculty members within a single academic division. Gifts or promise of gifts, in exchange for favorable terms

on a technology license or a first look at intellectual property may also pose a problem.

2. The acquisition of goods and services for the Institute represents a large portion of Caltech's expenditures. Purchasing goods and services from companies that sponsor research at the Institute, or who are licensees of Institute technology, may raise issues similar to those raised by large gifts from commercial sponsors.
3. A potential institutional conflict of interest exists simply by the Institute having a license agreement with, or an equity position in, a company sponsoring a faculty member's research. In these situations, there may be, or may appear to be, a bias to accept terms and conditions that would facilitate the company's success.

Reporting Institutional Conflicts of Interest

If you identify a situation that appears to be an Institutional Conflict of Interest, you should report the situation to either the Vice President for Business & Finance or to the Provost on campus or to the Associate Director for Business at JPL. You may also make a report by calling the campus Compliance Hotline at 626-395-8787 or the JPL Ethics Office at 818-354-6338 or submitting an http://hotline.caltech.edu/contact.

Disability and Reasonable Accommodation

It is the Institute's policy to comply fully with the Americans with Disabilities Act, the Rehabilitation Act , and other applicable federal and state laws to ensure equal opportunity for qualified persons with disabilities, including disabled veterans. The Institute does not discriminate based on physical or mental disability, and is committed to ensuring that there is no unlawful discrimination in any of its academic or employment programs, services, activities, and terms and conditions of employment.

As required by law, the Institute will make reasonable accommodations to qualified individuals with known disabilities including students, faculty, postdoctoral scholars, staff, and job applicants, so long as such accommodation does not create an undue hardship for the Institute. The Institute also will provide reasonable accommodations to employees with pregnancy-related conditions consistent with federal and state law.

The following individuals have been designated as contacts for disability related issues, and as coordinators under the Rehabilitation Act. Individuals who wish to request an accommodation should contact the appropriate Institute representative.

Students:
Barbara Green, 626-395-6351
Associate Dean of Students
Faculty:
Stacey Scoville, 626-395-6320
Administrator to the Provost

Staff and Postdoctoral Scholars:
Campus
Tracey Saruwatari, 626-395-5740
Disability and Leave Manager

JPL
Arlene Cass, 818-354-9750
Human Resources Consultant

As part of the Institute's commitment to make reasonable accommodations, the Institute will participate in a timely, good faith, interactive process with the individual and the appropriate Institute representative to determine effective reasonable accommodations, if any, that can be made in response to a request for accommodation. The Institute has the right to request documentation of the individual's disability. By working together in good faith, the Institute will attempt to implement reasonable accommodations that are appropriate and consistent with its legal requirements.

After engaging in the interactive process, and after the Institute has determined if a reasonable accommodation is available, an individual with a disability who disagrees with the Institute's determination may file an appeal. Appeal procedures may be obtained from the campus/JPL coordinators listed in this policy.

Employees and applicants also may file a complaint with the U.S. Equal Employment Opportunity Commission, the California Department of Fair Employment and Housing, and the U.S. Department of Labor, Office of Federal Contract Compliance Programs, or the U.S. Department of Education, Office for Civil Rights. Students may file complaints with the U.S. Department of Education Office for Civil Rights at (415) 486-5555 (or ocr.sanfrancisco@ed.gov) or (800) 421-3481 (or OCR@ed.gov).

Environment, Health, and Safety

The California Institute of Technology (Caltech or Institute) is committed to conducting activities in a manner that promotes the safety and health of faculty, staff, students, and visitors and minimizes risk to Caltech property. Activities at Caltech are to be conducted in accordance with the following guiding principles:

- The responsibility for implementing and maintaining a safe environment rests on all staff, faculty, students, and visitors at Caltech.
- Supervisors are responsible for establishing safe practices in their respective laboratories or workplaces and for providing safe equipment and facilities for staff, students, and visitors.
- All faculty, students, staff, and visitors are expected to follow proper and safe procedures, to report accidents promptly to their supervisor, including any unsafe conditions or practices.

- Institute activities must comply with all applicable federal, state, and local environmental and safety laws and regulations.
- Waste is minimized through efficient and appropriate use of resources and is disposed of in a way that protects individuals and the environment and complies with applicable regulations.
- Those who do business with Caltech, such as contractors, consultants and vendors, are responsible for performing their work on Caltech property in a manner that protects the Institute from environmental and safety risks.

Roles and Responsibilities

The Institute has the responsibility to establish policies and provide resources to ensure compliance with environmental and safety laws. Caltech performs this function through the following committees and administrative and management structure:

- Institute Environment, Health and Safety Committee (IEHSC)

The Institute Environment, Health and Safety Committee will serve as the primary source of policy guidance on all matters pertaining to environmental and workplace safety compliance and related regulatory developments.

The committee is responsible for making recommendations regarding the allocation of Institute resources so as to maintain environmental (air emissions, soil contamination, water discharges, hazardous waste management) and workplace safety compliance. In addition, the committee develops Institute environmental and safety policy recommendations for approval by the president and monitors developments through the Environment, Health, and Safety Office to ensure that Institute policies are observed, remain current, and are consistent with the anticipated changes in regulatory climate.

This committee also provides an annual report to the president, summarizing the status of environmental and safety programs and risks affecting the Institute.

- Environment, Health, and Safety Office (EHS)

The EHS provides technical, regulatory, and related advisory services to the Institute community. EHS works in partnership with the divisions and administrative offices to develop and implement safety programs that provide technical guidance and training support relevant to the operations of the laboratory or workplace, are practical to carry out, and comply with the law. This includes general orientation in prudent laboratory practices, emergency response procedures, occupational safety, and familiarity with Institute EHS policies and plans. EHS also initiates site reviews to assess potential hazards and determines effective controls, coordinates hazardous waste training and pickup, and helps analyze specific problems.

EHS, working closely with the Office of the General Counsel as appropriate, conducts accident investigations and investigates and reports environmental and safety incidents.

- Division chair and head of administrative office

Caltech consists of divisions conducting research and educational activities and administrative offices supporting the operations of the Institute. It is the responsibility of the division chair and the head of each administrative office to ensure their units conduct operations in accordance with applicable laws and regulations, and to implement the Institute's environmental and safety policies.

Each division chair and the head of each administrative office maintain responsibility for day-to-day management and implementation of their environmental and safety programs.

Each division chair and head of each administrative office can designate an individual with the authority to implement, manage, and enforce environmental and safety compliance programs within the division or administrative office. With guidance and assistance from EHS, the responsible individual (i.e. the division chair, administrative office head, or their designee) shall manage the environmental and safety activities in the division or department.

- Supervisor responsibilities (all Institute supervisors and faculty)

Each supervisor has responsibility for conducting operations in accordance with all applicable laws and regulations and Institute policies.

Faculty bear full responsibility for the safety of work undertaken in their labs but can designate an individual to implement and manage the day-to day activities related to environmental and safety practices within their research group.

With guidance and assistance from EHS, the responsibilities of supervisors include training and informing employees, students, and visitors about workplace-specific hazards and safety procedures; providing personal protective equipment; correcting violations; investigating incidents and complaints by employees and students; overseeing proper storage and disposal of hazardous materials; enforcing policies (including appropriately disciplining employees and students who violate environmental and safety requirements); and appropriately documenting activities and processes.

- Institute faculty, staff, students, and visitors

It is the responsibility of each individual to conduct activities at Caltech in compliance with all applicable government, Institute, and division or department policies, procedures and guidelines. The success of the Institute's environmental and safety management activities requires the active involvement of individuals through participation in training; compliance with established safety and environmental procedures; reporting hazards and potential violations of regulations; and recommending improvements.

It is the responsibility of all employees and students of the Institute to disclose fully any activity that may result in a violation of environmental and safety regulations, and to cooperatively participate in the investigation and remediation of any incidents.

- Contractors

It is the responsibility of those under contract, consultants, vendors, and contractors to conduct their activities at Caltech in adherence with sound safety practices and to comply with all applicable environmental and safety laws and regulations as well as Institute policies in their contracts.

Reporting

In matters of actual or potential regulatory enforcement action, investigations, or employee complaints, EHS, working closely with the Office of the General Counsel, coordinates the Institute's response to external regulatory agencies concerned with workplace health, safety, and environmental compliance. EHS, Institute management, and the Office of the General Counsel work closely to ensure that a unified and consistent Institute position is provided in response to a governmental inquiry, complaint, or lawsuit.

Any questions or concerns regarding compliance should be brought to the attention of the relevant supervisor or to the director of EHS. Alternatively, concerns can be raised with the appropriate division chair or vice president or the EHS office.

Enforcement

Governmental agencies have established increasingly strict policies to ensure compliance with environmental and safety regulations, including harsh civil penalties and individual criminal prosecution leading to possible imprisonment and substantial fines. Accordingly, the Institute expects all faculty, staff, and students to be vigilant in complying with all environmental and safety requirements to properly conduct their activities at the Institute.

Caltech views compliance with all laws, regulations, and Institute guidelines as conditions of employment, and violation of such requirements shall be considered grounds for disciplinary action, including termination of employment.

Fire Safety

It is the policy of the California Institute of Technology to comply with all applicable laws, regulations, codes, and standards in regard to fires, fire safety, and fire protection. The Institute recognizes that campus fire safety is vitally important to the Institute community, and thus is committed to maintaining a safe environment for faculty, staff, students, and other members of the Institute community.

The purpose of the Institute policy on fire safety is to provide guidelines for establishing and maintaining fire safety procedures with respect to the undergraduate and graduate student houses and dormitories (student living areas or student housing) at the Institute.

Please refer to http://www.studaff.caltech.edu/policies.htm for the complete text of the policy.

Mural Policy

Murals or anything that goes on walls or ceilings in the shared spaces of Caltech's resident houses should not involve offensive material, which includes language or images that reasonable persons would find offensive, that would reasonably interfere with other residents' enjoyment of the facility, and/or that violate Caltech's nondiscrimination or unlawful harassment policies or other Caltech policies. Examples of offensive material include language or images that are racist or sexist or that are derogatory on the basis of national origin, disability, age, religion, or sexual orientation. Graffiti or anything else that makes the houses look deteriorated or degraded is also not acceptable. Students must notify the Housing Office in advance of the intention to put up a mural and of its proposed location. Neither the Housing Office nor Student Activities and Programs (Student Life) will bear the cost of removal if a mural is put up without consultation or differs from the submitted design in ways that make it inappropriate. All murals must comply with the mural policy and be approved following the guidelines stated in the mural policy. For full mural policy text, see http://www.housing.caltech.edu/undergrad/mural_policy.asp.

Missing Students

Missing student policy and procedure have been established to assist in locating Caltech students living in on-campus housing who, based on the facts and circumstances known to Caltech, the Institute has determined to be missing. Please refer to http://www.studaff.caltech.edu/policies.htm for the complete text of the policy.

Nondiscrimination and Equal Employment Opportunity

Caltech is committed to equal opportunity for all persons without regard to sex, race, color, religion, national origin, citizenship, ancestry, age, marital status, physical or mental disability, medical condition, genetic information, pregnancy or perceived pregnancy, gender, gender identity or expression, sexual orientation, protected veteran status or any other characteristic or condition protected by the state and federal law. It is the policy of Caltech to provide a work and academic environment free of discrimination as required by federal and state law, including Title IX which prohibits discrimination based on sex in Caltech's educational programs and activities. Discrimination is an act or communication that interferes with an individual's or a group's ability to participate fully in the Caltech community on the basis of any protected condition or characteristic. Sex discrimination, including sexual harassment and sexual violence (e.g., sexual assault) are prohibited at Caltech. Harassment on the basis of any legally protected characteristic is a form of discrimination and is likewise prohibited by this policy. Caltech will take all reasonable steps to eliminate discrimination, harassment, and sexual violence in its work and academic environment.

Caltech is an equal employment opportunity and affirmative action employer and will, whenever possible, actively recruit and include for employment members of underrepresented minority groups, females, protected veterans or individuals with disabled veteran status, and otherwise qualified persons with disabilities. Caltech will hire, transfer, recruit, train and promote based on the qualifications of the individual to ensure equal consideration and fair treatment of all. All other employment actions, such as work assignments, appointments, compensation, evaluations, training, benefits, layoffs, and terminations are governed by this policy. Personnel actions will be reviewed to ensure adherence to this policy.

Caltech's Associate Vice President for Human Resources and JPL's Director for Human Resources have been assigned to direct the establishment of and to monitor the implementation of personnel procedures to guide our Affirmative Action programs. They will have responsibility to review and update the Affirmative Action plans annually, including responsibility for the audit and reporting system. A notice explaining Caltech's policies will remain posted.

The Provost has been designated as the Equal Employment Opportunity Coordinator for faculty, the Director of Employee & Organizational Development for campus staff, the Associate Deans of Students for undergraduate students, the Dean of Graduate Studies for graduate students, and the Director for Human Resources at the Jet Propulsion Laboratory for employees assigned there. The Assistant Vice President for Equity, Accessibility, and Inclusion Initiatives has been designated as Caltech's Title IX Coordinator. She can be reached at (626) 395-3132, email: TitleIXCoordinator@caltech.edu, or at her office in Room 230, Center for Student Services. The Title IX Coordinator is supported by three deputy coordinators. The Deputy Title IX Coordinator for faculty is Melany Hunt, the Deputy Title IX Coordinator for staff and postdoctoral scholars is Susan Conner, and the Deputy Title IX Coordinator for JPL is Richard Conti.

Inquiries concerning the interpretation and application of this policy should be referred to the appropriate designated individual. Management is responsible for monitoring decisions regarding personnel actions to ensure that these decisions are based solely on the individual's merit, and on legitimate, nondiscriminatory job requirements for the position in question and the reasonableness of any necessary accommodations for persons with a disability.

Anyone who witnesses or experiences conduct he/she believes to be in violation of this policy is urged to contact any of the above mentioned coordinators, the individuals identified in Caltech's harassment policy, the Caltech Employee & Organization Development office or JPL Employee Relations Group immediately. Complaints, including complaints under Title IX, will be investigated promptly using the Procedures Regarding Unlawful Harassment, including Sexual Violence. Individuals who violate this policy may be subject to disciplinary action up to and including termination of employment or expulsion.

In addition, an employee who believes he or she has been subject to harassment or discrimination has the right to file a complaint with the Federal Equal Employment Opportunity Commission or the California Department of Fair Employment and Housing, which have the authority to remedy violations. Employees, students and others participating in Caltech's educational programs and activities may file complaints with the U.S. Department of Education Office for Civil Rights at (415) 486-5555 (or ocr.sanfrancisco@ed.gov) or (800) 421-3481 (or OCR@ed.gov).

Employees and applicants shall not be subjected to harassment, intimidation, threats, coercion, discrimination, or retaliation because they have engaged in or may engage in any of the following activities: filing a complaint; assisting or participating in an investigation, compliance review, hearing or any other activity related to the administration of any federal, state, or local law requiring equal opportunity; opposing any act or practice made unlawful by any federal, state or local laws requiring equal opportunity; exercising any state legal right protected by federal, state or local law requiring equal opportunity.

To ensure equal employment opportunity and nondiscrimination, each member of the Caltech community must understand the importance of this policy and his/her responsibilities to contribute to its success. The President of Caltech fully supports the Institute's equal opportunity and affirmative action policies.

Related Policies and Procedures

- Unlawful Harassment
- Procedures Regarding Unlawful Harassment
- Sexual Violence
- Disability and Reasonable Accommodation

Sexual Violence

Policy

All members of the Caltech community have the right to be treated, and the responsibility to treat others, with dignity and respect. These principles are fundamental to the educational and intellectual mission of Caltech. Consistent with these principles, it is the policy of Caltech to provide a work and academic environment free of sexual violence.

All forms of sexual violence are considered to be serious offenses. A broad range of behaviors can be classified as sexual violence. Sexual violence can be committed by individuals of any gender, regardless of an individual's sexual orientation or gender identification, and can occur between individuals of the same gender or different genders, strangers or acquaintances, as well as people involved in intimate or sexual relationships. Sexual violence is defined as physical sexual acts perpetrated forcibly and/or against a person's will, or where the person is incapable of giving consent. Sexual violence includes rape, sexual assault, sexual assault with an object, forced sodomy, statutory rape, forced oral contact, sexual battery, sexual coercion, sexual intimidation, and the threat of sexual assault. Sexual violence for purposes of this policy also includes sexual exploitation, stalking, domestic violence and dating violence.

Sexual exploitation occurs when an individual(s) takes sexual advantage of another for his or her own or another's benefit or advantage. Stalking is a course of conduct directed at an individual that would cause a reasonable person to fear for his or safety or the safety of others, or suffer substantial emotional distress. Dating violence is any act of violence, or threatened act of violence, against a person who is (or has been) in a romantic or intimate relationship with the alleged perpetrator. Domestic violence is violence committed by a current or former spouse, by a person with whom the victim shares a child, who is or has cohabitated with the victim, or by person similarly situated to a spouse, and by any other person against someone who is protected from that person's acts under domestic or family violence laws.

Consent

Consent is a crucial component of the Caltech policy. Consent is the affirmative, conscious, voluntary, informed, and uncoerced agreement through words and/or actions, which a reasonable person would interpret as a willingness to participate in mutually agreed-upon sexual activity. Sexual activity should occur only when all participants willingly and affirmatively choose to engage in particular acts. It is the responsibility of the initiator of the sexual activity, at each stage, to obtain effective consent. The use of intimidation, coercion, threats, force, or violence negates any consent obtained.

Indications that consent is not present include, but are not limited to:

- A verbal "no" (no matter how indecisive) or resistance (no matter how passive)
- When physical force is used, or when there is a reasonable belief of the threat of physical force
- When any kind of coercion is present

Affirmative consent must be ongoing throughout a sexual activity and can be revoked at any time. The existence of a dating relationship between the persons involved, or the fact of past sexual relationship between them, should never by itself be assumed to be an indicator of consent. Consent cannot be inferred from silence, passivity or lack of active resistance. Consent cannot be inferred from consent to a prior or different activity. If consent is revoked, the other party must immediately stop whatever sexual activity is occurring.

A person will not be considered to have given consent if he or she is incapable of making an intentional decision to participate in a sexual activity, including being unconscious or asleep; incapacitated by drugs, alcohol, or medication so that the complainant could not understand the fact, nature or extent of the sexual activity; or if they are unable to communicate due to a mental or physical condition. A person is considered to be incapacitated when that person lacks the ability to make informed, rational judgments and decisions to engage in sexual activity. States of incapacitation include, but are not limited to, unconsciousness, sleep, and blackouts. Where alcohol or drugs are involved, incapacitation is defined with respect to how the alcohol or other drugs consumed affects a person's decision-making capacity, awareness of consequences, and ability to make fully informed judgments.

Being intoxicated or otherwise impaired does not diminish one's responsibility to obtain consent. The question is whether or not the person who initiated the sexual activity knew or whether a sober and reasonable person in the same position should have known whether the other person gave effective consent.

Scope

This policy applies to all students, faculty, staff, postdoctoral scholars, volunteers, interns, vendors, independent contractors, visitors and any other individuals regularly or temporarily employed, studying, living, visiting, or otherwise participating in Caltech's educational programs and activities or conducting business or having any official capacity with Caltech or on Caltech property.

This policy applies to sexual violence occurring on Caltech property and at Caltech sponsored events and in Caltech programs that take place off campus.

Prohibition against Discrimination

Sexual violence is a form of sex discrimination and is prohibited by Title IX of the Education Code and other federal and state laws. Caltech will not tolerate sexual violence, and is committed to educating the community in ways to prevent its occurrence.

Any Caltech community member who has experienced sexual violence, whether by a stranger or non-stranger, is encouraged to immediately report the incident to Caltech as well as local law enforcement, and to seek assistance from a medical provider. Reports to Caltech and law enforcement may be pursued simultaneously.

Members of the Caltech community are encouraged to report sexual violence regardless of where the incident occurred, or who committed it. Even if Caltech does not have jurisdiction over an alleged perpetrator, Caltech will still take prompt action to provide for the safety and wellbeing of the individual reporting and the campus community. Caltech will promptly investigate complaints to determine what occurred and take reasonable steps to remedy the effects of the sexual violence and prevent recurrence of the behavior. Caltech will provide assistance in notifying law enforcement if the individual who experienced sexual violence so chooses. An individual who has experienced sexual violence also has the right to decline to notify law enforcement or Caltech. Caltech has an obligation under State law to report incidents of sexual violence to law enforcement. Caltech will not report identifying information about the victim without the victim's consent after being notified of his or her right to have personally identifying information withheld. If the victim does not consent to be identified, personally identifying information about the accused also will not be provided.

Prohibition against Retaliation

No member of the Caltech community will be retaliated against for making a good-faith report of alleged harassment or for participating in an investigation, proceeding, or hearing conducted by Caltech, or by a state or federal agency. Overt or covert acts of retaliation, reprisal, interference, discrimination, intimidation or harassment against an individual or group for exercising their rights under Title IX is unlawful. Retaliation against any member of the Caltech community for exercising their rights under Title IX or this policy is strictly prohibited. Caltech will take steps to prevent retaliation and will take prompt and appropriate corrective action if retaliation occurs. Individuals who violate this policy may be subject to disciplinary action up to and including termination or expulsion.

Title IX Coordinator & Deputy Coordinators

The Title IX Coordinator is responsible for Caltech's overall response to sex discrimination, sexual harassment and sexual violence. The Title IX Coordinator oversees all Title IX complaints and identifies and addresses any patterns of systemic problems that arise. The Title IX Coordinator also oversees the application of Caltech's policies and implementation of the processes and procedures to resolve complaints of sexual violence to ensure consistent treatment of parties involved and prompt and equitable resolution of complaints. The Title IX Coordinator is supported by three Deputy Coordinators. The Title IX Coordinator and Deputy Coordinators can answer questions regarding Title IX.

Title IX Coordinator

Felicia Hunt (faculty, staff, JPL, postdoctoral scholars, and students)
Phone: (626) 395-6346
E-mail: TITLEIXCOORDINATOR@CALTECH.EDU
Office: 230 Center for Student Services

Contact information for the Deputy Title IX Coordinators is available in the attached procedures and at http://titleix.caltech.edu/coordinator.

Privacy v. Confidentiality
Caltech is committed to protecting the privacy of all individuals involved in a report of sexual violence. Caltech takes reasonable and appropriate steps to preserve the complainant's and respondent's privacy and protect the confidentiality of information. All Caltech employees who are involved in the Title IX response, including the Title IX Coordinator, Deputy Coordinators, and investigators, receive specific instruction about respecting and safeguarding private information. Throughout the process, every effort is made to protect the privacy interests of all individuals involved, in a manner consistent with the need for a thorough review of the matter.

Privacy generally means that information related to a report of sexual violence will only be shared with those individuals who have a "need to know" in order to assist in resolving the matter. These individuals will be discreet and will respect the privacy of all individuals involved.

Confidentiality means that information shared by an individual with designated campus or community professionals cannot be revealed to any other individual without the express permission of the individual. These campus and community professionals are listed under "Confidential Resources" in the policy. These individuals are prohibited from breaking confidentiality unless there is an imminent threat of harm to self or others or as otherwise legally required. When a report involves suspected abuse of a minor under the age of 18, these confidential resources are required by state law to notify child protective services and/or local law enforcement.

Options for Immediate Assistance & Preservation of Evidence
Because sexual violence may involve physical trauma and is a crime, you are urged to seek medical treatment as soon as possible. You are strongly encouraged to preserve all physical evidence of the assault. This may be needed to prove criminal sexual violence, or for obtaining a protective order. Do not shower, bathe, douche, eat, drink, wash your hands, or brush your teeth until after you have had a medical examination. Save all of the clothing you were wearing at the time of the assault. Place each item of clothing in a separate paper bag. Do not use plastic bags. Do not clean or disturb anything in the area where the assault occurred.

Caltech also encourages you to seek immediate psychological and support/advocacy services provided by campus and/or community services. Campus Security and the Protective Services Division at JPL will help you contact on-campus resources, provide you with information regarding off-campus resources for advocacy, medical treatment, and forensic evidence collection, and will provide you with taxi voucher to access the off-campus resources.

24-Hour a Day/7 Days a Week
Campus Security
(626) 395-5000

JPL Protective Services Division
(818) 393-3333
(818) 354-3333

If you want Security to contact a confidential campus resource for you (or at JPL for the JPL Protective Services Division to contact the JPL after hours Employee Assistance Program/Life Matters), you simply need to give them a number where the confidential resource can contact you. You do not have to provide your name or any information regarding the incident.

Peace Over Violence (24-hour emergency medical care and forensic services, counseling and psychotherapy, advocacy, and accompaniment services)
892 N. Fair Oaks Avenue, Suite D
Pasadena, CA 91103
(626) 584-6191
(626)793-3385 (24 hours)

San Gabriel Medical Center (for treatment and forensic evidence collection (the "rape kit")
438 West Las Tunas Drive
San Gabriel, CA 91776
(626) 289-5454
Sexual Assault Response Team (SART) Hotline: (877) 209-3049 (24 hours)

The Rape Treatment Center at Santa Monica-UCLA Medical Center
(24-hour emergency medical care and forensic services (the "rape kit")
(310) 319-4000
www.911rape.org
Huntington Memorial Hospital Emergency Room (24-hour emergency medical care)
100 W. California Blvd.
Pasadena, CA 91105
(626) 397-5112

Pasadena Police Department
207 N. Garfield Ave.
Pasadena, CA 91101
Call 911 for Emergency Response
Non-Emergency Response: (626) 744-4241

Note that medical providers (but not psychological counselors) in California are required to notify law enforcement when they receive a report of sexual assault.

Confidential Resources
Members of the Caltech community may access the offices below for confidential support. Counselors and designated confidential advocates in these offices will listen and help identify options and next steps. They can also help you decide what plan of action feels most comfortable. Talking to any of these individuals does not constitute reporting an incident to Caltech. Although they are not involved in Caltech's formal response to an incident, or possible legal action, staff members in each of these offices are available to provide support to a victim or accused as he or she moves through the steps related to either or both of these processes. Staff in these offices may be able to help you develop a clear statement that contains all of the relevant information regarding your complaint, or may recommend that you speak with another campus office for additional specialized services or resources, including how to obtain a protective order.

If a victim who speaks with a mental health professional or other confidential resource requests confidentiality, Caltech will be unable to conduct an investigation into the particular incident or pursue disciplinary action against the alleged perpetrator.

Even so, these mental-health professionals and other confidential resources will assist the victim in receiving other necessary protection and support, such as victim advocacy, academic support or accommodations, disability, health or mental health services, and changes to living, working or course schedules. A victim who at first requests confidentiality may later decide to file a complaint with Caltech and/or report the incident to law enforcement. These mental-health professionals and confidential resources will provide the victim with assistance in filing a complaint if the victim wishes to do so.

Mental-Health Professionals
Mental-health professionals in the Student Counseling Center and the Staff and Faculty Consultation Center provide mental-health counseling to the campus community. The JPL Employee Assistance Program/Life Matters provides mental-health counseling to the JPL community. They will not report any information about an incident to the Title IX Coordinator unless requested by their client. They may report aggregate statistics (with no identifying information) for inclusion in Caltech's Annual Security Report. They can be contacted 24 hours a day/7 days a week at:

- For students:
  (626) 395-8331 Student Counseling Center
  (626) 395-5000 after hours via Security

- For faculty, campus staff, and postdoctoral Scholars:
  (626) 395-8360 Staff and Faculty Consultation Center
  (626) 395-5000 after hours via Security

- For JPL employees:
  (818) 354-3680 JPL Employee Assistance Program (on site)
  (800) 367-7474 JPL Employee Assistance Program/Life Matters (off site and after hours)
  (818) 354-3333 after hours via JPL Protective Services Division
  (818) 393-3333

Other Campus Confidential Resources
Designated confidential resources at the Caltech Center for Diversity and the Health Educator's Office can generally talk to a victim without revealing any personally identifying information about an incident to Caltech. A victim can seek assistance and support from these individuals without triggering a Caltech investigation that could reveal the victim's identity or that the victim has disclosed the incident.

While maintaining a victim's confidentiality, the Caltech Center for Diversity and the Health Educator's Office will report the nature, date, time and general location of an incident to the Title IX Coordinator. This limited report, which includes no information that directly or indirectly identifies the victim, helps keep the Title IX Coordinator informed of the general extent and nature of sexual violence on- and off- campus so that coordinator can track patterns, evaluate the scope of the program and formulate appropriate campus-wide responses. These confidential resources may report aggregate statistics (with no identifying information) for inclusion in Caltech's Annual Security Report.

- Caltech Center for Diversity (students):
  (626) 395-5772 or (626) 395-8108
- Health Educator (students): (626) 395-2961

Reporting to Caltech
Caltech is required to take corrective action if a "responsible employee" knew or reasonably should have known about sexual violence. A "responsible employee" is a Caltech employee who has the authority to redress sexual violence, who has the duty to report incidents of sexual violence or other student misconduct, or whom a student or employee could reasonably believe has the authority or duty to do so.

When an individual tells a responsible employee about an incident of sexual violence, the responsible employee must report to the Title IX Coordinator or another individual listed below all relevant details about the alleged sexual violence. Caltech is committed to protecting the privacy of all individuals involved in a report of sexual violence. All employees involved in the response to a report of sexual violence understand the importance of properly safeguarding private information. Caltech will make every effort to protect individuals' privacy interests consistent with Caltech's obligation to investigate reports made to Caltech. Caltech will not share information with law enforcement that identifies the victim without the victim's consent.

The following individuals are responsible employees for reporting purposes.

Campus Responsible Employees:

Title IX Coordinator and Deputy Coordinators
Chief of Security
Director of Security Operations
Security Officers
Provost
Vice Provosts
Division Chairs
Division Administrators
Deans
Associate Deans
Student Affairs Directors
Master of Student Housing
Residence Life Coordinators
Resident Associates
Coaches
Director of Employee & Organization Development
Employee Relations Consultants
Associate Vice President of Human Resources
Department Heads
Faculty with administrative responsibilities

JPL Responsible Employees:

Title IX Coordinator and Deputy Coordinator
JPL Protective Services Group Supervisor, Investigations
Director for Human Resources
Deputy Director for Human Resources
Human Resources Business Partners
Section Managers

If you would like support and guidance in filing a complaint, please contact the Title IX Coordinator or a Deputy Coordinator, one of the Deans or Associate Deans, the Director of Employee & Organization Development in Human Resources, or the JPL Section Manager of Talent Management or Human Resources Business Partners at JPL.

No member of the Caltech community will be retaliated against for making a good-faith report of alleged sexual violence or for participating in an investigation, proceeding, or hearing conducted by Caltech, or by a state or federal agency.

Reports Involving Minors

Every member of the Caltech community who knows of, or reasonably suspects, child abuse, including sexual violence, has a personal responsibility to report to Caltech Security or the JPL Division of Protective Services immediately. Caltech employees who are mandatory reporters have additional reporting obligations, including reporting immediately to LA County Child Protection or the local police department. See the Violence Prevention policy for more information.

Anonymous Reporting
Although Caltech encourages victims to talk to someone, Caltech provides the following resources for anonymous reporting:

> Campus Hotline (626) 395-8787 or (888) 395-8787
> JPL Ethics Hotline (818) 354-9999
> JPL Protective Services Division's Workplace Violence Hotline (818) 393-2851

For either Campus or JPL by submitting a compliance HOTLINE CONTACT FORM

Campus Security can also receive anonymous reports of sexual violence at (626) 395-5000.

Contacting one of these anonymous reporting resources may trigger an investigation, and if you share personally identifying information, you will be notified if an investigation occurs.

Notification of Law Enforcement
Individuals who experience sexual violence are encouraged to notify local law enforcement. Caltech will provide assistance in reporting such incidents if the victim requests. Victims of sexual violence have the right not to notify law enforcement.

Caltech has an obligation under State law to report incidents of sexual violence to law enforcement. Caltech will not report identifying information about the victim without the victim's consent after being notified of his or her right to have personally identifying information withheld. If the victim does not consent to be identified, personally identifying information about the accused also will not be provided.

Requests for Confidentiality
If a member of the Caltech community discloses an incident to a responsible employee but requests that his or her name not be used or requests that no investigation into a particular incident be conducted or that no disciplinary action be taken, Caltech must weigh the request against its obligation to provide a safe, non-discriminatory environment. The Title IX Coordinator or designee will evaluate all requests for confidentiality once a responsible employee is on notice of the alleged sexual violence. Factors that the Title IX Coordinator or designee will consider include circumstances that suggest there is an increased risk of the alleged perpetrator committing additional acts of sexual violence or other violence. Factors may also include circumstances that suggest there is an increased risk of future acts of sexual violence under similar circumstances, whether there was a weapon involved, the age of a student victim, and whether there are other means to obtain relevant evidence.

Caltech will take all reasonable steps to investigate or otherwise determine what occurred and respond to the complaint consistent with the request not to use the complainant's name or request not to pursue an investigation or that no disciplinary action be taken, but its ability to do so may be limited based on the nature of the request by the complainant. When Caltech is unable to take action consistent with the request of the complainant, the Title IX Coordinator will inform the complainant about Caltech's chosen course of action, which may include Caltech seeking disciplinary action against the respondent. Alternatively, the course of action may also include steps to limit the effects of the alleged sexual violence and prevent its recurrence that do not involve formal disciplinary action against the respondent or revealing the identity of the complainant. If the complainant insists that his or her name not be disclosed to the respondent, the Title IX Coordinator will explain that Caltech's ability to respond may be limited, including pursing disciplinary action against the alleged perpetrator. The Title IX Coordinator will also advise the complainant that Caltech and Title IX prohibit retaliation, and that Caltech will take steps to prevent retaliation and responsive corrective action if it occurs. If the complaint includes allegations that may constitute a possible crime, the complainant will be notified of his or her right choose whether to file a criminal complaint.

Timely Warnings
In the event Caltech believes that there is a serious or continuing threat to the campus community, Caltech will issue a timely warning. Timely warnings will not disclose the name of the victim.

Clery Reporting
The Clery Act requires Caltech to issue an Annual Security Report, which includes crime statistics and information about campus crime prevention programs and policies. Campus Security gathers crime statistics from security reports, Pasadena Police Department information, and reports by Campus Security Authorities. Crime statistics do not disclose any identifying information about a complainant, respondent or third parties. Crimes reported in the Annual Security Report that are addressed by Title IX are forcible and non-forcible sexual offenses, stalking, dating violence, and domestic violence. For more information and statistics for the past three years, see the current Annual Security Report.

Contacting the Office of Civil Rights
Employees, students and others participating in Caltech's educational programs and activities may direct questions regarding Title IX or file complaints with the U.S. Department of Education Office for Civil Rights, (415) 486-5555, OCR.SANFRANCISCO@ED.GOV or (800) 421-3481, OCR@ED.GOV.

In addition, employees have the right to file a complaint with the Federal Equal Employment Opportunity Commission or the

California Department of Fair Employment and Housing, which have the authority to remedy violations.

Informational Resources

Information on harassment and sexual violence, as well as copies of Caltech's Sexual Violence, Nondiscrimination and Equal Employment Opportunity, Violence Prevention, and Unlawful Harassment policies are available from Caltech's Title IX Coordinator and Deputy Coordinators, Student Affairs and Deans offices, the Caltech Center for Diversity, Resident Associates, the Staff and Faculty Consultation Center, Employee & Organization Development at campus, and the Human Resources Business Partners and the Employee Assistance Program/Life Matters at JPL. The Policies are published in the Caltech Catalog and on the following Caltech websites: Caltech Human Resources, JPL Human Resources, Title IX, and Student Affairs.

Procedures for Responding to and Resolving Complaints of Sexual Violence at Caltech

Caltech will take prompt and appropriate action to address all reports of sexual violence in a fair and impartial manner. The complainant, respondent, and all other participants in the process will be treated with dignity, care and respect. All complaints of sexual violence will be handled promptly, fairly, thoroughly and impartially from the initial assessment through the resolution.

These procedures are for the benefit of the Caltech community and do not apply in cases involving complainants and/or respondents who are not current Caltech students, faculty, staff, postdoctoral scholars, volunteers, and interns. When a complaint involves a third party who is not affiliated with Caltech, Caltech's ability to investigate and take action against the perpetrator may be limited. However, in all cases, Caltech will conduct an inquiry into what occurred and take prompt action as is practicable to provide for the safety and well-being of the complainant and the campus community.

As used in these procedures, a complainant refers to the individual who is reported to be the subject of sexual violence. A respondent refers to the individual who reportedly committed the sexual violence. A third party refers to any other participant in the process, including a witness to the incident or an individual who makes a report on behalf of someone else.

Interim Measures

Upon receipt of a report of sexual violence, Caltech will take prompt measures to protect the rights of both the complainant and the respondent as appropriate. Caltech will immediately assess whether there is a threat to the complainant and/or other members of the community and will take steps necessary to address such risk. These steps may include interim safety measures to provide for the safety of individuals and the campus community.

Interim safety measures, administrative changes and/or academic changes can be made at any stage in the process to protect the rights of either party. They will be made by the appropriate administrators. These changes should be discussed with the appropriate responsible Caltech official: Provost, EOD Director, Deans, Associate Deans, Associate Vice President for Human Resources on campus, or Director for Human Resources at JPL. Changes affecting faculty, staff and employees at JPL might include transfer of supervisory or evaluative responsibility regarding grading, supervision, tenure review, letters of recommendation, and/or changes to office assignments. For students, these changes might include the complainant's option to avoid contact with the respondent via a "no contact" order from the Deans, changes to classes and/or housing, Caltech-imposed leave for the respondent, as well as any other remedy that can be tailored to the involved individuals to achieve the goals of this policy. When taking steps to separate a complainant and respondent, Caltech will endeavor to minimize the burden on the complainant. Care will be taken to protect both parties with the greatest degree of privacy possible. If a complainant wishes to seek a temporary restraining order or similar judicial order, Caltech will help the complainant with that process.

Measures for the broader student population may include but are not limited to: developing materials on sexual violence, further training for employees regarding Title IX, education of students on bystander intervention and/or sexual violence prevention, or taking steps to clearly communicate that Caltech does not tolerate sexual violence and will respond to any incidents and to any student who reports such incidents.

Prohibition against Retaliation

Retaliation against any member of the Caltech community involved in the process of responding to and resolving a report of sexual violence, including complainants, respondents and third parties, is strictly prohibited. Caltech recognizes that retaliation can take many forms, may be committed by or against an individual or group, and that a complainant, respondent or third party may commit or be the subject of retaliation. Caltech will take steps to prevent retaliation and will take prompt and appropriate corrective action to stop retaliation if it occurs.

False Reports

Caltech will not tolerate intentional false reporting of incidents. A good-faith complaint that results in a finding of "no violation" is not considered a false report. However, when a complainant or third party is found to have fabricated allegations or to have given false information with malicious intent or in bad faith, they may be subject to disciplinary action.

Amnesty for Student Alcohol or Drug Use

Caltech encourages reporting of sexual violence. It is in the best interests of the Caltech community that complainants and third parties report sexual assault to Caltech. To encourage reporting, a student or witness in an investigation will not be subject to disciplinary action for a violation of the honor code or Caltech's substance Abuse policy at or near the time of the incident, unless Caltech determines that the violation was egregious, including but not limited to, an action that places the health or safety of any other person at risk. Caltech may however, initiate an educational discussion or pursue other educational remedies regarding alcohol or drugs.

Making a Report to Caltech
A member of the Caltech community who wishes to report sexual violence should do so as soon as possible after the assault, although reports (hereinafter "complaints") may be made at any time. Complaints can be made orally or in writing. Complaints should be brought to the attention of one of the following individuals or other responsible employees listed in the policy.

Title IX Coordinator
Felicia Hunt (faculty, staff, postdoctoral scholars, and students)
Phone: (626) 395-6346
E-mail: TITLEIXCOORDINATOR@CALTECH.EDU
Office: 230 Center for Student Services

Deputy Title IX Coordinator for faculty
Melany Hunt
Phone: (626) 395-6339
E-mail: HUNT@CALTECH.EDU
Office: 104 Parsons Gates
Deputy Title IX Coordinator for staff and postdoctoral scholars
Susan Conner
Phone: (626) 395-5930
E-mail: SUSAN.CONNER@CALTECH.EDU
Office: 206 Central Engineering Services

Deputy Title IX Coordinator for JPL
Richard Conti
Phone: (818) 354-9837
E-mail: RICHARD.A.CONTI@JPL.NASA.GOV
Office: Human Resources T1720-164

Initial Title IX Assessment
For every report of sexual violence, Caltech's Title IX Coordinator will make an initial assessment of the complaint which will include an immediate assessment of any risk of harm to individuals or to the campus community and will take steps necessary to address those risks. These steps may include interim protective measures to provide for the safety of the complainant and the campus community as described above.

The complainant will be provided with information on the complainant's rights and options under the Institute's Sexual Violence policy and these procedures, written materials about the availability of, and contact information for, on- and off-campus resources and services, and coordination with law enforcement. The need for and types of interim measures also will be discussed.

The Title IX Coordinator may also meet with the respondent and other relevant parties as part of the initial assessment. If the Title IX Coordinator meets with the respondent, he or she be will provided with information on the respondent's rights and options under the Institute's Sexual Violence policy and these procedures, and written materials about the availability of, and contact information for campus resources and services.

The initial assessment will proceed to the point where a reasonable assessment of the safety of the individual and of the campus community can be made and an appropriate approach to resolution can be determined. Thereafter, the Title IX Coordinator may refer the complaint for formal investigation, administrative resolution or other appropriate disposition, depending on a variety of factors, such as the complainant's request that his or her name not be used, complainant's request that no investigation into a particular incident be conducted or that no disciplinary action be taken, the risk posed to any individual or the campus by not proceeding, the nature and seriousness of the allegations, whether there have been other reports/complaints of sexual violence involving the respondent, and whether the allegations are contested. The Title IX Coordinator will obtain the complainant's agreement to proceed with the proposed approach to resolution, whether it be a formal investigation, administrative resolution or another alternative approach.

Caltech will investigate reports of sexual violence consistent with its obligations under applicable law. For complaints solely covered by Title IX, the Title IX Coordinator will seek consent from the complainant to proceed with a formal investigation or an administrative resolution. If the complainant requests confidentiality or asks that the complaint not be pursued, Caltech will still take all reasonable steps to investigate or otherwise determine what occurred and respond to the report. If the complainant refuses to have his/her name disclosed to the respondent, the Title IX Coordinator will explain that Caltech's ability to investigate and respond may be limited. If the complaint includes allegations that may constitute a possible crime, the Title IX Coordinator will notify the complainant of his/her right to file a criminal complaint or to choose not to notify law enforcement.

Administrative Resolution

The Title IX Coordinator, with the complainant's and the respondent's agreement, may offer the opportunity to resolve the sexual violence complaint by Administrative Resolution. Administrative Resolution provides an opportunity for the respondent to accept responsibility for his or her alleged conduct and proceed to a resolution without a formal investigation.

If the Administrative Resolution option is agreed to by the complainant, the Title IX Coordinator will meet with the respondent to review the allegations. The Title IX Coordinator will provide the respondent with information on the respondent's rights and options under the Institute's Sexual Violence policy and these procedures, and written materials about the availability of, and contact information for campus resources and services. The Title IX Coordinator will offer the respondent the opportunity to resolve the complaint by Administrative Resolution by accepting responsibility for the alleged conduct. If the respondent elects to acknowledge that the alleged conduct occurred and takes responsibility for the alleged sexual violence, the respondent will sign a written acknowledgement and the matter will be referred to the appropriate Caltech official for a decision concerning sanctions and any other remedial action that may be appropriate. The complainant and respondent will both be notified simultaneously in writing of the resolution, including any sanctions against the respondent. Either party may appeal the sanction imposed.

If the respondent contests responsibility for the alleged conduct, the Administrative Resolution process will be concluded and the case will be referred for Formal Investigation or other resolution as appropriate.

Formal Investigation

The following procedures apply with respect to complaints referred for Formal Investigation:

- The purpose of the investigation is to determine the facts relating to the complaint.
- All participants involved in the investigation will receive a fair process and be treated with dignity, care, and respect.
- All parties may have an advisor of their choice accompany them when reporting, or responding to, allegations of sexual violence. The advisor may not speak on behalf of the party he or she is accompanying.
- Caltech's investigation will occur independently from any legal/criminal proceedings that may take place. Caltech may defer fact gathering for a short time during only the initial stages of a criminal investigation.
- The individuals involved in the investigation will respect the privacy of the complainant, respondent, and that of all parties involved while conducting a thorough review of the complaint.
- Investigators will be trained regularly in issues related to sexual violence and how to conduct an investigation process that protects the safety of all involved and promotes accountability. Caltech will typically use a team of two investigators, though an individual, a committee or an outside consultant may conduct the investigation. The investigators chosen must be impartial and free of any conflict of interest.
- The complainant and respondent will be informed of the relevant procedures, and may object to the investigator(s) by notifying the appropriate Caltech official in writing.
- If internal investigators are used, at least one investigator should be from the same area as the respondent.

- Within a reasonable length of time after the complaint has been filed, the respondent will be notified of the nature of the complaint, and an investigation will begin. If interim measures are needed to protect the rights of the complainant and/or respondent during the investigation, the appropriate administrators shall see that they are made.
- Caltech's policies on Sexual Violence, Nondiscrimination and Equal Employment Opportunity and Unlawful Harassment will be reviewed with both parties and copies will be provided to them.
- The complainant and respondent will be informed that Caltech will not tolerate retaliation, will take steps to prevent retaliation, and will take strong responsive action if retaliation occurs. The complainant and respondent will be advised to notify Caltech immediately of any retaliation that occurs. They should immediately notify any of the individuals to whom a complaint can be made if anyone associated with the matter is under continuing threat or is being subject to retaliation.
- The investigator(s) will summarize for the respondent the evidence in support of the complaint to allow the respondent the opportunity to reply.
- The investigation will be treated as private to the extent possible and all parties will be advised to maintain privacy. Caltech administrators will be informed on a need-to-know basis. Caltech will make reasonable and appropriate efforts to preserve the complainant's and respondent's privacy and protect the confidentiality of information.
- The complainant and respondent will be given equal opportunity to present their cases separately to the investigator(s), to suggest others who might be interviewed, and to present other evidence. The investigator(s) can, if appropriate, interview other parties to reach findings and conclusions.
- The investigators will investigate any allegations that alcohol or drugs were involved in the incident.
- The investigators will not ask questions or seek evidence of the complainant's prior sexual conduct with anyone other than the respondent. Furthermore, evidence of a prior consensual dating or sexual relationship between the complainant and respondent itself does not imply consent or preclude a finding of sexual violence.
- All parties who participate in investigative interviews may submit written statements. Investigatory meetings will not be recorded.
- Both parties will be kept informed of the status of the investigation.
- Complaints will be investigated and resolved within a reasonably prompt time frame after the complaint has been made, generally within 60 days (not including any appeal), though this time frame may be extended depending on factors, including

but not limited to, the complexity of the case.

- Investigative files will be maintained in the Title IX Coordinator's office.

Substance Abuse

The California Institute of Technology ("Caltech") is committed to providing a safe, healthy, and productive work and academic environment for all its faculty, staff, postdoctoral scholars and students. Consistent with its concern for the well-being of its faculty, staff, postdoctoral scholars and students, it is a Caltech policy to maintain a work and academic environment free from drug and alcohol abuse. Faculty, staff, postdoctoral scholars and students are required to comply with this policy and the related guidelines provided by the academic divisions and student organizations.

The unlawful manufacture, distribution, cultivation, dispensation, possession, sale, offer to sell, purchase, offer to purchase, and/or unlawful use of controlled substances* or alcohol on the Caltech campus or its offsite locations, including the Jet Propulsion Laboratory ("JPL"), or as any part of its activities, is prohibited. (*Controlled substances include, but are not limited to, marijuana, heroin, cocaine, LSD, and amphetamines.) In addition, every employee is required to remain free from the influence of controlled substances, alcohol, or any substance that may impair the employee's ability to perform his/her job duties safely or productively, or that may otherwise impair his/her senses, coordination, or judgment while on duty. Any employee reporting to work (or otherwise at work) under the influence of, or having present in his/her body, any prescribed drug, alcohol, or other substances or medication that may adversely affect the employee's ability to work in a safe, productive, or efficient manner, must advise his/her supervisor. Caltech may require an employee to submit to drug and alcohol testing consistent with Institute policy and applicable federal and state law.

As a condition of continued admission, every student is required to comply with this policy. As a condition of employment, all Caltech employee (this includes faculty, staff, postdoctoral scholars and student employees), regardless of their location, are required to comply with this policy. A Caltech employee who violates this policy will be subject to disciplinary action up to and including termination of employment. A violation of this policy is likely to result in termination, even for a first offense. Similarly, all students, not just student employees, should understand that disciplinary action including suspension or expulsion may be invoked for violation of this policy and that intoxication is never an excuse for misconduct. Legislation within the last ten years allows institutions of higher education to contact parents when their adult child violates a school's alcohol or drug policy. If a student's behavior with respect to alcohol and drugs presents a danger to himself/herself and/or others, Caltech may inform the parents.

A faculty, staff, postdoctoral scholar or student who is convicted (including a plea of nolo contendere [no contest]) of a criminal drug statute violation must, within five (5) calendar days after the conviction, notify Caltech of such conviction. A Campus employee should inform the Executive Director of Human Resources and students should inform his/her dean. A JPL employee should inform the People Services Section Manager in Human Resources.

Persons who are not employees of Caltech, but who perform work at Caltech for its benefit (such as contractors and their employees, temporary employees provided by agencies, visitors engaged in joint projects at Caltech, etc.), are required to comply with this policy. Violation of this policy is likely to result in being barred from the workplace even for a first offense.

Health Risks

The use of any mind-or mood-altering substance, including alcohol, can lead to psychological dependence which is defined as a need or craving for the substance and feelings of restlessness, tension, or anxiety when the substance is not used. In addition, with many substances, use can lead to physical tolerance, characterized by the need for increasing amounts of the substance to achieve the same effect and/or physical dependence, characterized by the onset of unpleasant or painful physiological symptoms when the substance is no longer being used. As tolerance and psychological or physical dependence develop, judgment becomes impaired and the individual often does not realize he/she is losing control over the use of the substance and that he/she needs help.

It is impossible to predict accurately how an individual will react to a specific drug or to alcohol because effects vary depending on the person, environmental variables, the dosage and potency of the substance, the method of taking the substance, the chronicity of use, and whether the substance is taken in conjunction with other substances. Illegal drugs have particularly unpredictable effects due to variability in dosage and purity. Further, the overall potency of street drugs has increased dramatically over the past two decades, making users increasingly susceptible to negative effects.

Alcohol acts as a depressant to the central nervous system and can cause serious short- and long-term damage. Short-term effects include nausea, vomiting, and ulcers; more chronic abuse can lead to brain, liver, kidney, and heart damage, and even to eventual death. Ingesting a large amount of alcohol at one time can lead to alcohol poisoning, coma, and death. Drugs such as LSD, amphetamines, marijuana, and alcohol alter emotion, cognition, perception, physiology, and behavior in a variety of ways. Health risks include but are not limited to depression, apathy, hallucinations, paranoia, and impaired judgment, and all substances have an adverse effect on pregnancy. When two or more substances are combined, the effect is often stronger than their additive sum.

Local, State, and Federal Legal Sanctions

Local, state, and federal laws establish severe penalties for violations of drug and alcohol statutes. These sanctions, upon conviction, may range from a fine to life imprisonment. In the case of possession and distribution of illegal drugs, these sanctions could include the seizure and summary forfeiture of property, including vehicles. It is especially important to know that federal laws have established penalties for illegally distributing drugs to include life imprisonment and fines in excess of $1,000,000. Some examples of local or state laws are as follows.

- Unlawful possession of a narcotic drug is punishable by imprisonment in the state prison.
- The purchase, possession, or consumption of any alcoholic beverages (including beer and wine) by any person under the age of 21 is prohibited.
- It is illegal to provide alcohol to a person under the age of 21.
- Serving alcohol to an intoxicated person is prohibited.
- Selling any alcoholic beverages, except under the authority of a California Alcoholic Beverage Control License, is prohibited.
- It is a felony to induce another person to take various drugs and "intoxicating agents" with the intent of enabling oneself or the drugged person to commit a felony. The person who induced the other may be regarded as a principal in any crime committed.
- Any person found in a public place to be under the influence of an intoxicating liquor or drug and unable to care for his/her own safety, or who is interfering with the use of a public way, is guilty of disorderly conduct, which is a misdemeanor.

Examples of local, state and federal laws and regulations may be accessed at the Caltech Security website.

In addition, pursuant to federal law, a student's eligibility for federal financial aid may be suspended if the student is convicted, under federal or state law, of any offense involving the possession or sale of illegal drugs.

Resources for Staff, Faculty, Postdoctoral Scholars and Students

Caltech recognizes drug and alcohol abuse and dependency as treatable conditions and offers faculty, staff, postdoctoral scholars and students support programs for individuals with substance use problems. Faculty, staff, and postdoctoral scholars are encouraged to seek assistance for drug- and alcohol-related problems through the Caltech Staff and Faculty Consultation Center (SFCC) at Campus and the Employee Assistance Program (EAP) at JPL. Individuals can contact the SFCC by calling (626) 395-8360, and the EAP by calling (818) 354-3680. Students are encouraged to seek assistance from the Student Counseling Center (SCC) at 626-395-8331. In addition, faculty, staff, postdoctoral scholars, and students can seek confidential referral information through the Center for Diversity at (626) 395-3221.

The staff of the SFCC, the EAP and the SCC will help employees and students to identify appropriate treatment resources and will refer them to counseling, treatment, or rehabilitation programs, as appropriate. Health insurance plans provide varying amounts of coverage for substance-abuse programs to address substance abuse and rehabilitation. Individuals may contact their health providers or Caltech Human Resources Benefits office at Campus at (626) 395-6443, or JPL at (818) 393-3191, for plan details. Information obtained regarding a faculty, staff, postdoctoral scholar or student during voluntary participation in services at the SFCC, EAP, SCC, or any related program will be treated as strictly confidential, and no information, including whether or not an individual is receiving services, will be shared with third parties, except by written consent or as required by law.

Drug and Alcohol Awareness Program
Caltech has established and will maintain a drug and alcohol awareness program to educate faculty, staff, postdoctoral scholars and students about:

1. Caltech's substance abuse policy;
2. the dangers of drugs and alcohol in a work and academic environment;
3. faculty, staff, postdoctoral scholar and student assistance pr grams; and
4. disciplinary action that may be imposed on faculty, staff, postdoctoral scholars and students for violations of this policy.

Caltech will distribute to all faculty, staff, postdoctoral scholars and students a copy of this policy on an annual basis.

Supervisor's Responsibilities
If an employee is suspected of violating this policy, the employee's supervisor should consult with the Director of EOD at Campus or the People Services Section Manager in Human Resources at JPL regarding appropriate actions, which may include an investigation, and discipline up to and including termination. If a supervisor believes an employee's behavior raises safety concerns for the employee or others, the supervisor must take immediate action, including calling EOD on campus or the People Services Section in Human Resources at JPL, to assess and address the situation and to remove the employee from the worksite if necessary.

Caltech Sanctions
Caltech will impose sanctions on individuals and/or organizations that violate this policy. These sanctions will be consistently enforced and penalties will depend on the severity of the offenses. Penalties can include employment termination and student suspension or expulsion from Caltech and referral for prosecution for the most serious viola-

tions of the law and this policy. Disciplinary action may be invoked entirely apart from any civil or criminal penalties that the faculty, staff, postdoctoral scholars and students might incur.

Unlawful Harassment

It is the policy of Caltech to provide a work and academic environment free of unlawful harassment ("harassment") and retaliation. Harassment is the creation of a hostile or intimidating environment in which inappropriate conduct, because of its severity and/or persistence, is likely to interfere with an individual's work or education, or affect adversely an individual's living conditions. Harassment in any form, based on sex, race, color, age, national origin, ethnicity, ancestry, physical or mental disability, medical condition genetic information, pregnancy, marital status, religion, gender, gender expression or identity, sexual orientation, protected veteran status, or any other characteristic protected by state or federal laws, is unlawful and is strictly prohibited, as are all forms of sexual intimidation, exploitation, and violence. All faculty, students, staff, postdoctoral scholars and others participating in Caltech's educational programs and activities, whether they take place in Caltech facilities, or elsewhere, should be aware that Caltech does not tolerate any conduct that constitutes harassment or retaliation. Caltech promptly and thoroughly investigates complaints of harassment consistent with legal requirements, and takes appropriate action, including disciplinary measures, when warranted.

Caltech requires any employee, who is responsible for directing or supervising other Caltech employees or evaluating the work of students, to regularly participate in training regarding harassment, including sexual harassment, and the prevention of abusive conduct, consistent with federal and state legal requirements.

Some kinds of behavior that are clearly intended to harass, while inappropriate and not tolerated at Caltech, may not be unlawful. Behavior evidently intended to dishonor such characteristics as race, gender, gender expression or identity, national origin or ethnic group, religious belief, sexual orientation, age, or disability is contrary to the pursuit of inquiry and education and may be discriminatory harassment and violate the law. These types of behavior may be dealt with through the student disciplinary process or through supervisory intervention, including the Caltech progressive disciplinary process. However, in order to make an accurate judgment as to whether incidents are unlawful, the full context in which the actions were taken or statements made must be considered.

Sexual Harassment is a Form of Unlawful Harassment

Sexual harassment is a form of sex discrimination and is unlawful, violating Title VII of the Civil Rights Act of 1964, as amended, Title IX of the Education Code, and California law.

Sexual harassment is defined as unwelcome sexual advances, requests for sexual favors, and other verbal or physical conduct of a sexual nature, by a stranger or non-stranger, when:

1. Submission to such conduct is made either explicitly or implicitly a term or condition of an individual's employment or education.
2. Submission to or rejection of such conduct by an individual is used as the basis for decisions affecting that individual.
3. Such conduct has the purpose or effect of unreasonably interfering with an individual's performance or creating an intimidating, hostile, or offensive environment.

Sexual harassment by peers, coworkers, managers or third parties such as nonemployees, vendors, or contractors is a form of prohibited sex discrimination where the objectionable conduct creates a hostile educational or work environment. All individuals are protected against sexual harassment regardless of gender, sexual orientation or gender identification. Moreover, sexual harassment is prohibited regardless of the sex of the harasser, e.g., even where the harasser and the person being harassed are members of the same sex.

Examples of Sexual Harassment
Some examples of conduct that may constitute sexual harassment are:

- Unwanted sexual advances.
- Offering employment or research benefits in exchange for sexual favors.
- Making or threatening reprisals after a negative response to sexual advances.
- Making sexual gestures, or displaying sexually suggestive objects, pictures, cartoons, posters, calendars, or computer screens.
- Downloading, viewing, and/or sharing of pornography.
- Making or using derogatory comments, epithets, slurs, or jokes of a sexual nature.
- Using Caltech resources (including electronic resources) or time to create or obtain sexually explicit materials that are not directly related to legitimate business of Caltech.
- Surreptitiously taking pictures or videos of an individual's body for sexual purposes.
- Verbal abuse of a sexual nature, graphic comments about an individual's body, sexually degrading words used to describe an individual, suggestive or obscene letters, notes, electronic mail messages, or invitations.
- Unwelcome, intentional, and/or repeated touching of a sexual nature.
- Ostracizing individuals from group activities because of their sex or because they objected to harassing behavior.

Even when relationships are consensual, care must be taken to eliminate the potential for harassment or other conflicts. It is not acceptable to treat other employees, who are not in the consensual relationship, less favorably. Caltech practice, as well as more general ethical principles, prohibits individuals from evaluating the work or academic performance of those with whom they have amorous and/or sexual relationships, or from making hiring, salary, or similar decisions.

Upon learning about such a relationship, the supervisor, dean, or division chair has the authority and responsibility to review and remedy any direct administrative or academic relationship between the involved individuals.

When a consensual personal relationship arises and a power differential exists, consent may not be considered a defense in a claim that Caltech's unlawful harassment policy has been violated. The individual in the relationship with greater power will be held responsible.

Scope

This policy applies to all students, faculty, staff, postdoctoral scholars, volunteers, interns, vendors, independent contractors, visitors and any other individuals regularly or temporarily employed, studying, living, visiting, or otherwise participating in Caltech's educational programs and activities or conducting business or having any official capacity with Caltech or on Caltech property.

Prohibition against Retaliation

No member of the Caltech community will be retaliated against for making a good-faith report of alleged harassment or for participating in an investigation, proceeding, or hearing conducted by Caltech, or by a state or federal agency. Overt or covert acts of retaliation, reprisal, interference, discrimination, intimidation or harassment against an individual or group for exercising their rights under Title IX are unlawful. Retaliation against any member of the Caltech community for exercising their rights under Title IX or this policy is strictly prohibited. Caltech will take steps to prevent retaliation and will not be tolerated and will be subject to prompt and appropriate corrective action if retaliation occurs. Individuals who violate this policy may be subject to disciplinary action up to and including termination or expulsion.

Title IX Coordinator & Deputy Coordinators

The Title IX Coordinator is responsible for Caltech's overall response to sex discrimination, sexual harassment and sexual violence. The Title IX Coordinator oversees all Title IX complaints and identifies and addresses any patterns or systemic problems that arise. The Title IX Coordinator also oversees the application of Caltech's policies and implementation of the process and procedures to resolve complaints of sexual harassment under Title IX to ensure consistent treatment of parties involved and prompt and equitable resolution of complaints. The Title IX Coordinator is supported by three Deputy Coordinators. The Title IX Coordinator and Deputy Coordinators can answer questions regarding Title IX.

Title IX Coordinator
Felicia Hunt (faculty, staff, JPL, postdoctoral scholars, and students)
Phone: (626) 395-6346
E-mail: TitleIXCoordinator@caltech.edu
Office: 230 Center for Student Services

Contact information for the Deputy Title IX Coordinators is available in the attached procedures and at http://titleix.caltech.edu/coordinator.

Privacy v. Confidentiality
Caltech is committed to protecting the privacy of all individuals involved in a report of harassment. Caltech takes reasonable and appropriate steps to protect the complainant's and respondent's privacy and protect the confidentiality of information. All Caltech employees who are involved in the response, including the Title IX Coordinator, Deputy Coordinators, and investigators, receive specific instruction about respecting and safeguarding private information. Throughout the process, every effort is made to protect the privacy interests of all individuals involved, in a manner consistent with the need for a thorough review of the matter.

Privacy generally means that information related to a report of harassment will only be shared with those individuals who have a "need to know" in order to assist in the matter. These individuals will be discreet and will respect the privacy of all individuals involved.

Confidentiality means that information shared by an individual with designated campus or community professionals cannot be revealed to any other individual without the express permission of the individual. These professionals are listed under "Confidential Resources" in the policy. These individuals are prohibited from breaking confidentiality unless there is an imminent threat of harm to self or others or as otherwise legally required. When a report involves suspected abuse of a minor under the age of 18, these confidential resources are required by state law to notify child protective services and/or local law enforcement.

Confidential Resources
Caltech offers members of the Caltech community the choice of seeking confidential counseling outside Caltech's formal mechanisms for resolving unlawful harassment complaints. These confidential counseling services are intended for the personal benefit of the individual and offer a setting where various courses of action can be explored and are listed below.

Mental-Health Professionals
Mental-health professionals in the Student Counseling Center and the Staff and Faculty Consultation Center provide mental-health counseling to the campus community. The JPL Employee Assistance Program/Life Matters provides mental-health counseling to the JPL

community. They will not report any information about an incident to the Caltech, including the Title IX Coordinator unless requested by their client. They may report aggregate statistics (with no identifying information) for inclusion in Caltech's Annual Security Report. They can be contacted 24 hours a day/7 days a week at:

- For students:
  (626) 395-8331 Student Counseling Center
  (626) 395-5000 after hours via Security

- For faculty, campus staff, and postdoctoral Scholars:
  (626) 395-8360 Staff and Faculty Consultation Center
  (626) 395-5000 after hours via Security

- For JPL employees:
  (818) 354-3680 JPL Employee Assistance Program (on site)
  (800) 367-7474 JPL Employee Assistance Program/Life Matters (off site and after hours)
  (818) 354-3333 after hours via JPL Protective Services Division
  (818) 393-3333

Other Campus Confidential Resources
Certain individuals in the Caltech Center for Diversity and the Health Educator's Office have been designated as confidential resources for purposes of Title IX. These designated individuals can generally talk to a victim of sexual harassment without revealing any personally identifying information about an incident to Caltech. A victim can seek assistance and support from these individuals for sexual harassment incidents without triggering a Caltech investigation that could reveal the victim's identity or that the victim has disclosed the incident.

While maintaining a victim's confidentiality in cases involving allegations of sexual harassment, the Caltech Center for Diversity and the Health Educator's Office will report the nature, date, time and general location of an incident to the Title IX Coordinator. This limited report, which includes no information that directly or indirectly identifies the victim, helps keep the Title IX Coordinator informed of the general extent and nature of sexual harassment on- and off- campus so that coordinator can track patterns, evaluate the scope of the program and formulate appropriate campus-wide responses. These confidential resources may report aggregate statistics (with no identifying information) for inclusion in Caltech's Annual Security Report.

- Caltech Center for Diversity (students):
  (626) 395-5772 or (626) 395-8108
- Health Educator (students):
  (626) 395-2961

Reporting
Anyone who witnesses or experiences or is otherwise aware of conduct that he or she believes to be in violation of this policy, including retaliation, is urged to contact Caltech immediately. For a list of individuals to whom violations of this policy can be reported, please see the Title IX Coordinator information above and other individuals identified in the attached Procedures.

Individuals also may report harassment anonymously by contacting the Caltech Hotline at (626) 395-8787 or (888) 395-8787 or the JPL Ethics Hotline at (818) 354-9999, or by submitting a compliance hotline form.

Reports Involving Minors
Every member of the Caltech community who knows of, or reasonably suspects, child abuse, including sexual harassment, has a personal responsibility to report to Caltech Security or the JPL Division of Protective Services immediately. Caltech employees who are mandatory reporters have additional reporting obligations, including reporting immediately to LA County Child Protection or the local police department. See the Violence Prevention policy for more information.

Contacting the Outside Agencies
In addition, an employee who believes he or she has been unlawfully harassed has the right to file a complaint with the federal Equal Employment Opportunity Commission or the California Department of Fair Employment and Housing which have the authority to remedy violations. Employees, students and others participating in Caltech's educational programs and activities may file complaints with the U.S. Department of Education Office for Civil Rights (415) 486-5555, ocr.sanfrancisco@ed.gov or (800) 421-3481 or OCR@ed.gov.

Procedures for Investigating and Resolving Unlawful Harassment Complaints at Caltech
These procedures apply to complaints of unlawful harassment ("harassment"). There are several courses of action available to address complaints of harassment, each with different consequences and implications with respect to confidentiality and resultant action. These options are not mutually exclusive. The complainant may choose which course to follow and may submit a formal complaint at any time.

These procedures are for the benefit of the Caltech community and do not apply in cases involving complainants and/or respondents who are not current Caltech students, faculty, staff, postdoctoral scholars, volunteers, and interns. When a complaint involves a third party who is not affiliated with Caltech, Caltech's ability to investigate and take action against the person accused of harassment may be limited. However, in all cases, Caltech will conduct an inquiry into what occurred and take prompt action as is practicable to provide for the safety and well-being of the complainant and the campus community.

As used in these procedures, a complainant refers to the individual who is reported to be the subject of harassment. A respondent refers to the individual who reportedly committed the harassment. A third party refers to any other participant in the process, including a witness to the incident or an individual who makes a report on behalf of someone else.

Prohibition against Retaliation

Retaliation against any member of the Caltech community involved in the process of responding to and resolving a report of harassment, including complainants, respondents and third parties, is strictly prohibited. Caltech recognizes that retaliation can take many forms, may be committed by or against an individual or group, and that a complainant, respondent or third party may commit or be the subject of retaliation. Caltech will take steps to prevent retaliation and will take prompt and appropriate corrective action to stop retaliation if it occurs.

False Reports

Caltech will not tolerate intentional false reporting of incidents. A good-faith complaint that results in a finding of "no violation" is not considered a false report. However, when a complainant or third party is found to have fabricated allegations or to have given false information with malicious intent or in bad faith, they may be subject to disciplinary action.

Informal Options

An individual who believes that he or she has been harassed may choose to resolve his or her concerns informally. In general, the goal of the informal options is to quickly end offending behavior without utilizing disciplinary action. Individuals with an official status at Caltech, such as faculty, managers, or supervisors, are expected to follow up with the complainant to make sure that the issue has indeed been resolved. Mutually agreeable administrative changes are sometimes possible to ease an uncomfortable situation. Individuals are not required to try to resolve their concerns informally before making a formal complaint.

Complainants should consider at the outset whether such changes might be desirable. Informal options include:

- Talking personally with the offending individual, or writing a letter asking him or her to stop. This is a personal step taken solely among the relevant parties.

- Speaking to members of the Student Counseling Center, the Staff and Faculty Consultation Center, or the Caltech Center for Diversity on campus and the JPL Employee Assistance Program/ Life Matters at JPL. Such conversations are confidential and are not communicated to individuals within or outside Caltech.

- Resolving the complaint informally with the help of a third party who has a faculty, supervisory, or managerial position at Caltech. The goal here is also to allow the parties to resolve complaints without an investigation and without elevating the complaint within Caltech. However, a person in one of these official positions is obligated to follow up to be sure the situation has been resolved. This action might include referring the complaint to an appropriate individual within Caltech or sharing some of this information with other persons holding positions of responsibility at Caltech.

Formal Complaints
A formal complaint is a request that Caltech take action. The complainant may file a formal complaint by reporting the offending conduct to individuals holding any of the positions listed below.

Campus:
Title IX Coordinator and Deputy Coordinators
Chief of Security
Director of Security Operations
Security Officers
Provost
Vice Provosts
Division Chairs
Division Administrators
Deans
Associate Deans
Student Affairs Directors
Master of Student Housing
Residence Life Coordinators
Resident Associates
Coaches
Director of Employee & Organization Development
Employee Relations Consultants
Associate Vice President of Human Resources
Department Heads
JPL:
Title IX Coordinator and Deputy Coordinator
JPL Protective Services Group Supervisor, Investigations
Director for Human Resources
Deputy Director for Human Resources
Human Resources Business Partners
Section Managers

Responsible Employees
The employees listed above are responsible employees for purposes of Title IX as well as faculty with administrative responsibilities. Pursuant to Title IX, Caltech is required to take corrective action if a "responsible employee" knew or reasonably should have known about sexual harassment. A "responsible employee" is a Caltech employee

who has the authority to redress sexual harassment, who has the duty to report incidents of sexual harassment or other student misconduct, or who a student or employee could reasonably believe has the authority or duty to do so.

When an individual reports an incident of sexual harassment to a responsible employee, he or she must report to the Title IX Coordinator all relevant details about the alleged sexual harassment. Caltech is committed to protecting the privacy of all individuals involved in a report of sexual harassment. All employees involved in the response to a report of sexual harassment understand the importance of properly safeguarding private information. Caltech will make every effort to protect individuals' privacy interests consistent with Caltech's obligation to investigate reports made to Caltech. Caltech will not share information with law enforcement that identifies the victim without the victim's consent.

If a member of the Caltech community discloses an incident to a responsible employee but requests that his or her name not be used or requests that no investigation into a particular incident be conducted or that no disciplinary action be taken, Caltech must weigh the request against its obligation to provide a safe, non-discriminatory environment. The Title IX Coordinator or designee will evaluate all requests for confidentiality once a responsible employee is on notice of the alleged sexual harassment. Factors that the Title IX Coordinator or designee will consider include circumstances that suggest there is an increased risk of the accused committing additional acts of sexual harassment.

Caltech will take all reasonable steps to investigate or otherwise determine what occurred and respond to the complaint consistent with the request not to use the complainant's name or request not to pursue an investigation or that no disciplinary action be taken, but its ability to do so may be limited based on the nature of the request by the complainant. When Caltech is unable to take action consistent with the request of the complainant, the Title IX Coordinator will inform the complainant about Caltech's chosen course of action, which may include Caltech seeking disciplinary action against the respondent. Alternatively, the course of action may also include steps to limit the effects of the alleged sexual harassment and prevent its recurrence that do not involve formal disciplinary action against the respondent or revealing the identity of the complainant. If the complainant insists that his or her name not be disclosed to the respondent, the Title IX Coordinator will explain that Caltech's ability to respond may be limited, including pursing disciplinary action against the person accused of harassment. The Title IX Coordinator will also advise the complainant that Caltech and Title IX prohibit retaliation, and that Caltech will take steps to prevent retaliation and responsive corrective action if it occurs. If the complaint includes allegations that may constitute a possible crime, the complainant will be notified of his or her right choose whether to file a criminal complaint.

Anonymous Reporting
Although Caltech encourages victims to talk to someone, Caltech provides the following resources for anonymous reporting:

Campus Hotline	(626) 395-8787 or (888) 395-8787
JPL Ethics Hotline	(818) 354-9999
JPL Protective Services Division's Workplace Violence Hotline	(818) 393-2851

For either Campus or JPL by submitting a compliance HOTLINE CONTACT FORM

Campus Security can also receive anonymous reports of sexual harassment at (626) 395-5000.

Contacting one of these anonymous reporting resources may trigger an investigation, and if you share personally identifying information, you will be notified if an investigation occurs.

Processing Complaints
The complaint is then taken to the Provost, Director of EOD, or Dean(s) as appropriate (for faculty, postdoctoral scholars and staff, and students, respectively) at campus or the Section Manager, Talent Management at JPL, or their designees. Complaints of sexual harassment will be taken to the Title IX Coordinator or designee. The responsible administrator will initiate an investigation, or other action as described more fully below. Formal complaints of harassment can be made orally or in writing.

Caltech may initiate an investigation about an incident if it becomes aware that inappropriate conduct may have occurred. Caltech also will not delay its investigation of complaints of inappropriate conduct because of a law enforcement investigation.

Amnesty for Student Alcohol or Drug Use
Caltech encourages reporting of harassment, including sexual harassment. It is in the best interests of the Caltech community that complainants and third parties report sexual harassment to Caltech. To encourage reporting, a complainant or witness in an investigation will not be subject to disciplinary action for a violation of the honor code or Caltech's Substance Abuse policy at or near the time of the incident, unless Caltech determines that the violation was egregious, including but not limited to, an action that places the health or safety of any other person at risk. Caltech may however, initiate an educational discussion or pursue other educational remedies regarding alcohol or drugs.

Initial Title IX Assessment
For every report of sexual harassment covered by Title IX, Caltech's Title IX Coordinator will make an initial assessment of the complaint, which will include an immediate assessment of any risk of harm to individuals or to the campus community and will take steps necessary to address those risks. These steps may include interim protective

measures to provide for the safety of the complainant and the campus community as described above.

The complainant will be provided with information on the complainant's rights and options under the Institute's Unlawful Harassment policy and these procedures, written materials about the availability of, and contact information for, on- and off-campus resources and services, and coordination with law enforcement if appropriate. The need for and types of interim measures also will be discussed.

The Title IX Coordinator may also meet with the respondent and other relevant parties as part of the initial assessment. If the Title IX Coordinator meets with the respondent, he or she be will provided with information on the respondent's rights and options under the Institute's Sexual Violence policy and these procedures, and written materials about the availability of, and contact information for campus resources and services.

The initial assessment will proceed to the point where a reasonable assessment of the safety of the individual and of the campus community can be made and an appropriate approach to resolution can be determined. Thereafter, the Title IX Coordinator may refer the complaint for formal investigation, administrative resolution or other appropriate disposition, depending on a variety of factors, such as the complainant's request that his or her name not be used, complainant's request that no investigation into a particular incident be conducted or that no disciplinary action be taken, the risk posed to any individual or the campus by not proceeding, the nature and seriousness of the allegations, whether there have been other reports/complaints of sexual harassment involving the respondent, and whether the allegations are contested. The Title IX Coordinator will obtain the complainant's agreement to proceed with the proposed approach to resolution, whether it be a formal investigation, administrative resolution or another alternative approach. In implementing the approach, the Title IX Coordinator will inform and coordinate with the appropriate responsible Caltech official(s): Provost, EOD Director, Deans, Associate Deans, Associate Vice President for Human Resources on campus, or Director for Human Resources at JPL.

Caltech will investigate reports of sexual harassment consistent with its obligations under applicable law. For complaints solely covered by Title IX, the Title IX Coordinator will seek consent from the complainant to proceed with a formal investigation or an administrative resolution. If the complainant requests confidentiality or asks that the complaint not be pursued, Caltech will still take all reasonable steps to investigate or otherwise determine what occurred and respond to the report. If the complainant refuses to have his/her name disclosed to the respondent, the Title IX Coordinator will explain that Caltech's ability to investigate and respond may be limited. If the complaint includes allegations that may constitute a possible crime, the Title IX Coordinator will notify the complainant of his/her right to file a criminal complaint or to choose not to notify law enforcement.

Interim Measures

Upon receipt of a report of sexual harassment, Caltech will take prompt measures to protect the rights of both the complainant and the respondent as appropriate. Caltech will immediately assess whether there is a threat to the complainant and/or other members of the community and will take steps necessary to address such risk. These steps may include interim safety measures to provide for the safety of individuals and the campus community.

Interim safety measures, administrative changes and/or academic changes can be made at any stage in the process to protect the rights of either party. They will be made by the appropriate administrators. These changes should be discussed with the appropriate responsible Caltech official: Provost, EOD Director, Deans, Associate Deans, and Associate Vice President for Human Resources on campus, or Director for Human Resources at JPL. Changes affecting faculty, staff and employees at JPL might include transfer of supervisory or evaluative responsibility regarding grading, supervision, tenure review, letters of recommendation, and/or changes to office assignments. For students, these changes might include the complainant's option to avoid contact with the respondent via a "no contact" order from the Deans, changes to classes and/or housing, Caltech-imposed leave for the respondent, as well as any other remedy that can be tailored to the involved individuals to achieve the goals of this policy. When taking steps to separate a complainant and respondent, Caltech will endeavor to minimize the burden on the complainant. Care will be taken to protect both parties with the greatest degree of privacy possible. If a complainant wishes to seek a temporary restraining order or similar judicial order, Caltech will help the complainant with that process.

Measures for the broader student population may include but are not limited to: developing materials on sexual harassment, further training for employees regarding Title IX, education of students on bystander intervention and/or sexual harassment prevention, or taking steps to clearly communicate that Caltech does not tolerate sexual harassment and will respond to any incidents and to any student who reports such incidents.

Formal Investigation

The following procedures apply with respect to complaints referred for formal investigation:

- The purpose of the investigation is to determine the facts relating to the complaint.
- All participants involved in the investigation will receive a fair process and be treated with care and respect.
- All parties may have an advisor of their choice accompany them when reporting, or responding to, allegations of harassment. The advisor may not speak on behalf of the party he or she is accompanying.

- Caltech's investigation will occur independently from any legal/criminal proceedings that may take place. Caltech may defer fact gathering for a short time during the initial stages of a criminal investigation.
- The individuals involved in the investigation will respect the privacy of the complainant, respondent, and that of all parties involved while conducting a thorough review of the complaint.
- Investigators will train regularly, and at least annually, in issues related to harassment, and are trained how to conduct an investigation process that protects the safety of all involved and promotes accountability. Caltech will typically use a team of two investigators, though an individual, a committee or an outside consultant may conduct the investigation. The investigators chosen must be impartial and free of any conflict of interest.
- The complainant and respondent will be informed of the relevant procedures, and may object to the investigator(s) by notifying the appropriate Caltech official in writing.
- If internal investigators are used, at least one investigator should be from the same area as the respondent.
- Within a reasonable length of time the respondent will be notified of the nature of the complaint, and an investigation will begin. If interim measures are needed to protect the rights of the complainant or respondent during the investigation, the appropriate administrators shall see that they are made.
- In cases involving allegations of sexual harassment, Caltech's policies on Sexual Violence, Nondiscrimination and Equal Employment Opportunity and Unlawful Harassment will be reviewed with both parties and copies will be provided to them. In cases involving other forms of harassment, Caltech's Nondiscrimination and Equal Employment Opportunity policy will be reviewed with both parties and copies will be provided to them.
- The complainant and respondent will be informed that Caltech will not tolerate retaliation, will take steps to prevent retaliation, and will take strong responsive action if retaliation occurs. The complainant and respondent will be advised to notify Caltech immediately if any retaliation occurs. They should immediately notify any of the individuals to whom a complaint can be made if anyone associated with the matter is under continuing threat or is being subjected to retaliation.
- The investigator(s) will summarize for the respondent the evidence in support of the complaint to allow the respondent the opportunity to respond.
- The investigation will be treated as private to the extent possible and all parties will be advised to maintain privacy. Caltech administrators will be informed on a need-to-know basis. Caltech will make reasonable and appropriate efforts to preserve the complainant's and respondent's privacy and protect the confidentiality of information.

- The complainant and respondent will be given equal opportunity to present their case separately to the investigator(s), to suggest others who might be interviewed, and to present other evidence. Subsequently, the investigator(s) can, if appropriate, interview other parties to reach findings and conclusions.
- The investigators will investigate any allegations that alcohol or drugs were involved in the incident.
- In cases involving allegations of sexual harassment, the investigators will not ask questions or seek evidence of the complainant's prior sexual conduct with anyone other than the respondent. Furthermore, evidence of a prior consensual dating or sexual relationship between the complainant and respondent itself does not imply consent or preclude a finding of sexual harassment or violence.
- All parties who participate in investigative interviews may submit written statements. Investigatory meetings will not be recorded.
- Both parties will be kept informed of the status of the investigation.
- Complaints will be investigated within a reasonable length of time after the complaint has been made, normally within 60 days. An individual, a committee, or an outside consultant may conduct the investigation.
- Investigative files for sexual harassment complaints will be maintained in the Title IX Coordinator's office. Investigative files for other forms of harassment will be maintained in the appropriate administrator's office.
- Extensions of time, and other exceptions to or modification of these procedures can be made by the Title IX Coordinator, Provost, Dean or Associate Deans, Associate Vice President for Human Resources, or Director for Human Resources at JPL, if required for fairness or practical necessity. Exceptions must be made in writing and notice provided to both the complainant and respondent, which notice will include the reason for the extension, exception or modification.

The investigator(s) will use the preponderance of evidence standard in determining whether prohibited harassment occurred. A preponderance of the evidence means that it is more likely than not that the incident occurred. When the investigator(s) is presented with two different but plausible versions of the incident, credibility determinations may affect the outcome.

Findings and Conclusions

The investigator(their findings and conclusions to the relevant Dean, Provost, Executive Director of Human Resources, or Talent Management Manager at JPL, as appropriate, for decision.

The conclusions that the investigation might reach include, but are not limited to, the following possibilities. In each case the investigator(s) should summarize the evidence that supports the conclusion.

1. A violation of Caltech's Nondiscrimination and EEO, Unlawful Harassment or Sexual Violence Policies occurred.
2. Inappropriate behavior occurred, but did not constitute a violation of Caltech's policies on discrimination, harassment, and/or sexual violence. For example, the respondent improperly used the power of his or her position, used poor judgment, or violated applicable standards of ethical behavior.
3. The charges were not supported by the evidence.
4. The charges were brought without any basis or without a reasonable, good faith belief that a basis existed.

Resolution

As soon as practicable after receiving the findings and conclusions of the investigator(s), the appropriate Caltech official, the Provost for faculty, the relevant Dean for students, the Executive Director of Human Resources for postdocs and campus staff, or Deputy Director for Human Resources at JPL for JPL employees, will make a decision concerning resolution of the complaint, including imposing sanctions against the respondent if appropriate. The complainant and respondent simultaneously will be informed in writing, of the results, any changes to the results that occurs prior to the results becoming final, and when such results become final, and their right to appeal, the procedure for appeal. Any sanctions imposed will only be disclosed consistent with applicable law, including FERPA, Title IX of the Education Code, and the Clery Act.

If a violation of Caltech's Nondiscrimination and EEO, Unlawful Harassment or Sexual Violence policies has occurred, appropriate sanctions will be imposed if possible. Depending on the severity of the case and role at Caltech, possible sanctions include, but are not limited to:

- Verbal counseling or warning/training
- A formal written warning placed in the respondent's file
- Suspension of the right to accept new graduate students or postdoctoral scholars
- Transfer of advisees
- Removal from positions of administrative responsibility
- Removal from student housing
- Removal from a supervisory position
- Enforced leave of absence/suspension
- Termination of employment
- Expulsion/permanent dismissal

If the respondent was not found to have violated Caltech policy on harassment, but the investigation concludes that he or she violated another Caltech policy, or committed some other wrongful or improper act, corrective action will be taken. Effective corrective action may also require remedies for the complainant and/or the broader Caltech community. Caltech will take appropriate measures to prevent the reoccurrence of any sexual harassment, and to correct any discriminatory effects on the complainant and others, as appropriate.

Administrative Resolution

In cases where sexual harassment is alleged, the Title IX Coordinator, with the complainant's and the respondent's agreement, may offer the opportunity to resolve the sexual harassment complaint by Administrative Resolution. Administrative Resolution provides an opportunity for the respondent to accept responsibility for his or her alleged conduct and proceed to a resolution without a formal investigation.

If the Administrative Resolution option is agreed to by the complainant, the Title IX Coordinator will meet with the respondent to review the allegations. The Title IX Coordinator will provide the respondent with information on the respondent's rights and options under the Institute's Unlawful Harassment policy and these procedures, written materials about the availability of, and contact information for campus resources and services. The Title IX Coordinator will offer the respondent the opportunity to resolve the complaint by Administrative Resolution by accepting responsibility for the alleged conduct. If the respondent elects to acknowledge that the alleged conduct occurred and takes responsibility for the alleged sexual harassment, the respondent will sign a written acknowledgement and the matter will be referred to the appropriate Caltech official for a decision concerning sanctions and any other remedial action that may be appropriate. The complainant and respondent will both be notified simultaneously in writing of the resolution, including any sanctions against the respondent. Either party may appeal the sanction imposed.

If the respondent contests responsibility for the alleged conduct, the Administrative Resolution process will be concluded and the case will be referred for Formal Investigation.

Appeals

Appeals must be in writing and submitted within thirty (30) days of notification of the decision. Appeals of decisions resulting from the Formal Investigation process must be on the grounds that a procedural error occurred that significantly affected the outcome of the investigation, there is new and relevant evidence that was unavailable at the time of the investigation that could substantially impact the original findings, or the sanction is substantially disproportionate to the findings. Appeals of decisions resulting from the Administrative Resolution process must be made on the grounds that the sanction is substantially disproportionate to the acknowledged conduct. The complainant and the respondent simultaneously will be informed, in writing, of the outcome of the appeal. Appeal decisions are final.

Faculty complainants may appeal the decision to the Provost or designee; staff and postdoctoral scholars may appeal to the Vice

President for Human Resources or designee; students may appeal to the Vice President for Student Affairs or designee; and JPL employees may appeal to the JPL Director for Human Resources or designee.

Appeals by a faculty member of decisions or actions by the Provost that affect academic freedom and tenure can be made to the Faculty Committee on Academic Freedom and Tenure, as indicated in Chapter 4 of the Faculty Handbook.

Further Complaints

If the corrective action does not end the harassment, or if any retaliatory action occurs, the complainant should immediately notify the Title IX Coordinator, or for campus, the Provost or Division Chair, Dean or Associate Deans, or EOD Director; or for JPL, the Employee Relations Manager. In such cases, the complainant has the right to file another complaint.

Related Policies and Procedures:

- Nondiscrimination and Equal Employment Opportunity
- Sexual Violence Policy
- Violence Prevention

Violence Prevention

It is the policy of the Institute to provide a safe and secure environment for all members of the Institute community, comprising employees including faculty, students, postdoctoral scholars, and third parties, including minors by maintaining an environment of respect, providing conflict resolution processes, and by establishing preventative measures as well as providing assistance and support to victims. This policy specifically addresses the Institute's position on the prevention, reduction, and management of violence to provide a safe working and learning environment for its students, employees including faculty, postdoctoral scholars, and third parties engaged in any Institute activity.

All members of the Institute community shall cooperate to maintain a safe environment.

The Institute does not tolerate violence or threats of violence committed by or against employees including faculty, students, postdoctoral scholars, or third parties, including minors on its campus, at JPL or at any Institute locations or Institute activities. All weapons are banned from Institute premises and activities unless written permission is given by Campus Security or Jet Propulsion Laboratory (JPL) Division of Protective Services. Employees and students who violate this policy will be subject to corrective action, up to and including termination, expulsion/dismissal, or denial of access to Institute locations. Individuals who intentionally bring false accusations about a violation of this Policy against another also will be subject to corrective action, including termination or expulsion/dismissal. Other violations of the policy will be handled in accordance with Institute policies and applicable laws.

Caltech has established and will maintain a violence prevention program to educate employees including faculty, postdoctoral scholars and students about violence prevention and public safety awareness. This prevention program will include information on identifying and report child abuse.

1. Definitions
    1. Acts of violence include any physical action, whether intentional or reckless, that harms or threatens the safety of another individual at the Institute.
    2. A threat of violence includes any behavior that by its very nature could be interpreted by a reasonable person as intent to cause physical harm to another individual.
    3. Child abuse includes serious endangerment of a child's physical or mental health due to injury by act or omission (neglect), including acts of sexual abuse.
    4. Institute or Facilities include all Institute locations and off-campus locations where employees including faculty, postdoctoral scholars or students are engaged in Institute activities or programs.
    5. An At-Risk Individual is an employee, student, or other person who is a potential target or victim of violence. An At-Risk Individual also may be a threat to self or others.
    6. Intimidation is engaging in actions that include, but are not limited to, stalking or behavior intended to frighten, coerce or induce duress.
    7. Minor is anyone under the age of 18 years (also referred to as a "child" or "children").
    8. Mandatory Reporter is an employee who is required by law to make a report to the appropriate authorities whenever, within their professional capacity, or within the scope of their employment, they have knowledge of or observe a child they know or reasonably suspect has been the victim of child abuse. Certain professionals have long been Mandatory Reporters, but the law has recently been expanded such that any Institute employee whose duties bring them into direct contact with children under 18 years of age on a regular basis or who supervises employees whose duties bring them into contact with children on a regular basis is a Mandatory Reporter.
    9. Persons include Institute employees, including faculty, students, postdoctoral scholars, and third parties.
    10. Third Parties are individuals who are not Institute employees or students, such as relatives, acquaintances, guests, contractual personnel, consultants, vendors, visitors, volunteers, customers, clients, others engaging in sponsored activities, external affiliates, or others.
    11. Victim is an individual who has experienced or witnessed an act or acts of violence or threats of violence or intimidation as outlined in this Policy.

12. Weapon is any instrument or substance capable of producing bodily harm, in any manner, under any circumstances, and at a time and place that manifests intent to harm or intimidate another person or that warrants alarm for the safety of another person.

2. Examples of actions or activities that violate the Institute's Policy include, but are not limited to:
    1. Physical violence or the threat of physical violence against persons or property.
    2. Any verbal or physical conduct and/or harassing or intimidating behavior that causes a person to reasonably fear for his or her safety, or the safety of others including the safety of friends or family.
    3. Possessing, brandishing, or using a weapon in a manner that is not required by the individual's position while involved in any Institute activity on or off premises.
    4. Threatening or intimidating communications including otes, voice messages, telephone calls, electronic communications such as emails, texts and social media, and intra-office or regular mail directed towards a person(s) or Facilities.
    5. Intimidation, including stalking a person.
    6. Intentional destruction or threat of destruction to property owned or controlled by the Institute or NASA.
    7. Acts of violence or threats of violence, on or off Institute premises, if the threats or acts affect the legitimate interests of the Institute.

3. Reporting Violence
    1. Any individual who experiences or observes a threat, an act of violence, child abuse, or an unauthorized wea on must immediately notify Campus Security or JPL Protective Services Division, or law enforcement.

Campus Security	626-395-5000
JPL Protective Services Division	818-354-3530

An individual at a non-campus or non-JPL location must immediately notify local law enforcement.

2. If an individual becomes aware of behavior that might violate this Policy, the individual must immediately notify one of the following managers or offices.

Employee's supervisor/management	
Campus Human Resources –	
Employee Relations	626-395-8039
Dean of Students	626-395-6351
Dean of Graduate Studies	626-395-6346

Provost's Office	626-395-6320
Title IX Coordinator	626-395-3132
Campus Security	626 395-5000
Caltech Ethics Help Line	626-395-8787
JPL Human Resources	818-354-7506
JPL Protective Services Div.	818-354-3530
JPL Workplace Violence Hotline	818-393-2851
JPL Ethics Help Line	818-354-9999

3. The Institute will handle all reports of violence in a confidential manner, with information released as determined to be appropriate by the Institute.
4. Managers are required to immediately report any known incidents of violent, threatening, or intimidating behavior to Security, JPL Division of Protective Services, Human Resources, the Deans or the Provost, whether that behavior is observed on or off Institute premises when any Institute activity is involved.
5. Caltech policy prohibits retaliation against any employee, student, or third party who, in good faith, reports a violation or suspected violation of this Policy.

4. Reporting Child Abuse
    1. Every member of the Caltech community who knows of, or reasonably suspects, child abuse has a personal responsibility to report to Caltech Security or JPL Division of Protective Services immediately.
    2. Mandatory Reporters have the additional responsibility to report immediately or as soon as practicably possible by telephone to the LA County Child Protection Hotline (800) 540-4000 [or from out of state (213) 639-4500] or Pasadena Police Department 911 (for emergencies) or (626) 744-4501 (for non-emergencies), or to another local police department. Mandatory Reporters must file a written Suspected Child Abuse Report (SCAR) within 36 hours of receiving information concerning the incident. The SCAR can be completed online at https://mandreptla.org
    3. Mandatory Reports are required to attend training provided by the Institute and to sign an "Employee Acknowledgement of Mandatory Reporter Status".

5. Investigating Violence
    1. All reports of inappropriate behavior or conduct that violates or appears to violate any aspect of this Policy will be taken seriously, properly investigated and dealt with accordingly. Separate from any criminal investigation that the police may conduct, Campus Security or JPL Division of Protective Services, Human Resources,

the Deans, the Provost, or the Title IX Coordinator will conduct an independent investigation of the alleged threat or incident.

2. Based on the findings of the investigation, individuals who violate any aspect of this Policy may be subject to corrective action up to and including any of the following: termination of employment, expulsion/dismissal, removal from the premises, or being restricted from access to Institute facilities.
3. Additionally, the commission of such acts that may violate California or federal laws may be referred to law enforcement agencies for investigation.

6. Possession and Use of Firearms and Weapons

No unauthorized firearms or other weapons shall be brought onto Institute or NASA property or to Institute activities, with the exception of weapons authorized by the Chief of Security on campus or the Division Manager of the Protective Services Division at JPL.

7. Resources

The Staff and Faculty Consultation Center and the Student Counseling Center at campus or the Employee Assistance Program at JPL may provide resources such as intervention, consultation or referral for clinical evaluation or treatment, including arranging for counselors to work with at-risk individuals, and victims and observers of an incident.

Campus

Security	626-395-5000
Staff and Faculty Consultation Center	626-395-8360
Human Resources	626-395-8039
Dean of Students	626-395-6351
Dean of Graduate Studies	626-395-6346
Student Counseling Center	626-395-8331
Provost	626-395-6320
Title IX Coordinator	626-395-3132
Caltech Center for Diversity	626-395-6207
Caltech Ethics Help Line	626-395-8787

JPL

Protective Services Division	818-354-3530
Human Resources	818-354-7506
Employee Assistance Program	818-354-3680
Ethics	818-354-6338
Ethics Help Line	818-354-9999
Workplace Violence Hotline	818-393-2851

8. Exceptions

Any exception to this policy requires the approval of the Chief of Security for campus, or the Division Manager for the Division of Protective Services for JPL.

9. Related Policies

- Termination
- Unlawful Harassment
- Sexual Violence

Whistleblower Policy

It is important to the Institute that employees disclose violations or potential violations of law or serious breaches of conduct without the fear of retaliation. Caltech policy prohibits retaliation against an individual who makes a good faith disclosure of suspected wrongful conduct. Any individual who engages in retaliation in violation of this policy will be subject to disciplinary action up to and including termination or expulsion.

It is Caltech's policy to comply with applicable laws and regulations, including whistleblower protections provided under 41 USC Section 4712. As employees of the Institute, each of us is responsible for making sure his or her conduct fully complies with all laws and regulations as well as Institute policies. The Institute expects employees with knowledge of specific acts that he or she reasonably believes violate the law or Institute policy to disclose those acts to an appropriate Institute official.

If an employee believes he or she has been the subject of retaliation for making a good-faith disclosure, he or she is encouraged to contact his or her supervisor or one of the following offices: Human Resources, JPL Ethics Office, Audit Services and Institute Compliance, or the Office of General Counsel. Anyone with questions or concerns regarding inappropriate or improper activities within the Institute may use one of the anonymous reporting mechanisms outlined below.

Web Hotline:
http://asic.caltech.edu/hotline.htm

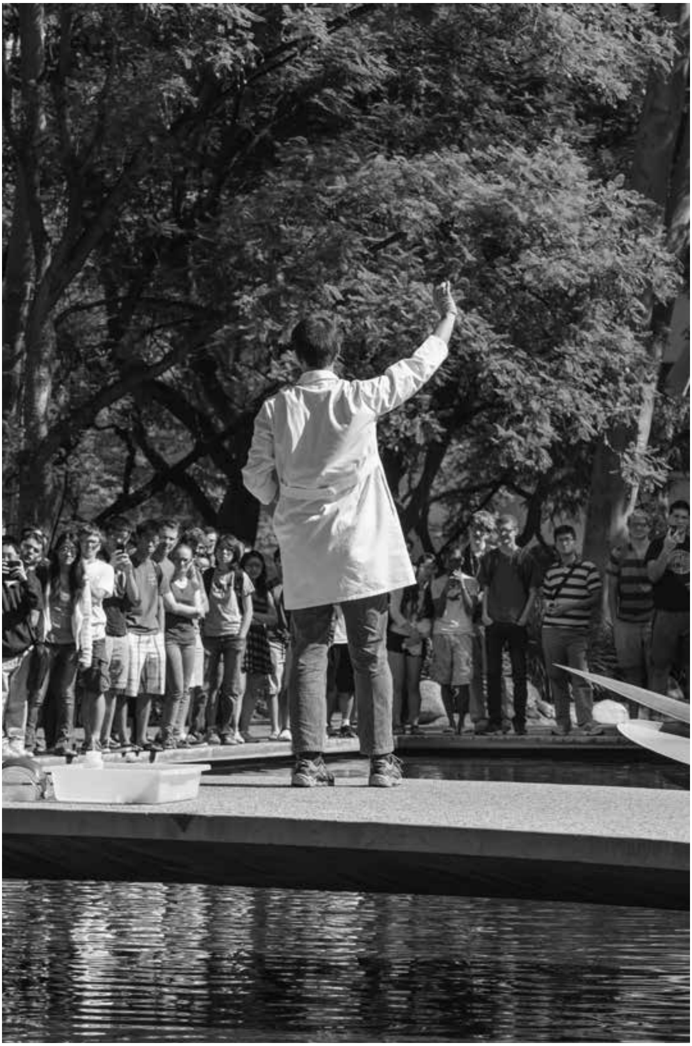
Telephone Hotline:
(626) 395-8787 or Toll Free (888) 395-8787

Interoffice Mail:
Audit Services and Institute Compliance
MC 250-64

U.S. Mail:
Audit Services and Institute Compliance
565 S. Wilson Avenue, Pasadena, CA 91106

JPL Ethics Line:
(818) 354-9999 or Toll Free (866) G0JPLEO

Areas of Study and Research



AEROSPACE

The Guggenheim Aeronautical Laboratory, the Kármán Laboratory of Fluid Mechanics and Jet Propulsion, and the Firestone Flight Sciences Laboratory form the Graduate Aerospace Laboratories, widely known as GALCIT. In this complex are housed the solid mechanics, impact mechanics, and deployable space structures laboratories, the hypersonics and hydrodynamics facilities, the explosion dynamics and detonation physics laboratories, and the Joe and Edwina Charyk Laboratory of Bioinspired Design and Biopropulsion, as well as the various disciplines making up the broad field known as aerospace.

Areas of Research

Aerospace has evolved at Caltech from a field of basic research and engineering, primarily related to the development of the airplane, into a wide discipline encompassing a broad spectrum of basic as well as applied problems in fluid dynamics and mechanics of solids and materials. Educational and research thrusts include the application of mechanics to various aspects of space exploration and to the study of biosystems and biopropulsion. Research at GALCIT has traditionally pioneered exploration of areas that have anticipated subsequent technological demands. This tradition places a high premium on in-depth understanding of fields both closely and remotely related to the behavior of fluids, solids, combustion, materials, and structures, such as physics, applied and computational mathematics, earthquake physics, atmospheric studies, materials science, micro- and optoelectronics, microfluidics, bioinspired design, biomedical devices, and even astrophysics. GALCIT students are known and sought after for their broad yet intense education and for their ability to deal with new and challenging problems.

Major areas of experimental, theoretical, and numerical research currently pursued by aerospace students at Caltech are briefly described below.

- *Mechanics of Lightweight Space Structures.* Current efforts in the field of next-generation deployable space structures aim to increase reliability and also lower fabrication and assembly costs by moving toward structures that consist of only a small number of separate pieces able to undergo large elastic deformations. These elastic–stored-energy structures return to their original, unstressed configuration when they are released in orbit. The design of these structures requires accurate structural models that incorporate geometry change and contact effects in sufficient detail to capture the actual behavior that is observed in ground tests. Local and global instabilities are often observed during folding/deployment, and their effects can also be very important. Ultimately, validation against space-based experiments will be pursued for a selected number of structural configurations. In parallel to these studies, thermomechanical constitutive models for ultrathin composite materials for these novel deployable space structures are being developed. Extensive studies of the deployment, elastic, and viscoelastic stability of stratospheric balloons are also being conducted.

- *Physics of Fluids.* Fluid dynamics as a discipline is as much a part of physics as of engineering. Physics of fluids refers to research in areas closer to applied physics than to direct technical applications. Present active research includes studies in gas dynamics and hypervelocity flows, diffraction and focusing of shock waves, detonation waves, shock-induced Rayleigh-Taylor and Richtmeyer-Meshkov instabilities, transient supersonic jets, the development of laser-scattering diagnostic techniques for fluid-flow measurements, the study of structures and mechanics in transition and turbulence, studies of two-phase flows and turbulent mixing, chemically reacting flows, and experimental manipulation and control of wall-bounded flows for improved flow characteristics, such as reduction of drag, noise, and structural loading.
- *Physics of Solids and Mechanics of Materials.* Mechanics of materials research involves both the quasi-static and dynamic characterization of the mechanical behavior and failure of solids. In order to understand materials for applications in a wide range of structures germane to aerospace as well as other engineering disciplines, both the physical foundations of that behavior and the mathematical or numerical representation of such behavior needs to be understood. Accordingly, studies involve material response at both the macroscopic (continuum) scales and the micro- and nanoscales. Of interest are the typical engineering metals, multiphase (composite) materials, polymers and ceramics, thin film materials used in microelectronic and optoelectronic applications, soft tissue mechanics of materials, and active materials used in structural actuation and controls. Other areas of active research include the study of highly nonlinear dynamics in solids, multiscale acoustic metamaterials, the analysis and design of mechanical metamaterials for the extreme conditions in air and space applications, and nondestructive evaluation/structural health monitoring of structures.
- *Space Technology.* The goal of industrial utilization and exploration of space requires that one addresses a wide range of engineering problems. Examples of research activities include lightweight structures for large aperture systems, in-space manufacturing, material and structural behavior in extreme temperature and radiation environments, spacecraft shielding against hypervelocity impact threats, the mechanics of sample containment for planetary protection, low-g biomechanics, biomimetics of locomotion in planetary atmospheres, hypersonic reentry into planetary atmospheres, in-space propulsion, guidance, navigation and control, and launch-vehicle performance and safety. Opportunities exist for research in collaboration with the Jet Propulsion Laboratory.

- *Computational Solid Mechanics.* Computational solid mechanics addresses phenomena ranging from the atomistic scale, e.g., nanostructured materials or nanoscale structures and devices, to the structural scale, e.g., fracture of aircraft or spacecraft components, modeling of large space structures or even dynamic fragmentation phenomena accompanying hypervelocity impact. It provides an indispensable tool for understanding the relation between structure and mechanical properties of materials, for predicting the efficiency of such industrial processes as machining and metal forming, and for assessing the safety of such structures as airplanes, spacecraft, automobiles, and bridges. The goals and objectives of this activity are to provide a state-of-the-art environment for the development of numerical methods in solid mechanics, to provide the computational resources required for large-scale simulations in solid mechanics, and to serve as an instructional facility for advanced courses.
- *Computational and Theoretical Fluid Dynamics.* Many of the fluid dynamics phenomena studied experimentally at GALCIT are also being investigated by numerical simulation and by theoretical analysis. Present active research areas in computational and theoretical techniques include direct numerical simulation, particle methods for flow simulation, new algorithms and subgrid-scale models for compressible and incompressible flows, large-eddy simulation methods, flows with shocks and driven by shocks, analytical and computational techniques for turbulence structure diagnostics, analysis of turbulent mixing dynamics, high-explosive interactions with deformable boundaries, chemically reacting flows, and detailed chemical reaction kinetics in flames and detonations.
- *Mechanics of Fracture.* An active effort is being made to understand mechanisms in a wide range of fracture problems. Aspects that are studied include quasi-static and dynamic crack growth phenomena in brittle and plastically deforming solids, polymers and advanced composites, as well as fatigue and failure of adhesive bonds. Research areas adjunct to dynamic fracture studies are those of dynamic localization in metals and of failure in frictional interfaces. These include the study of shear rupture phenomena in both coherent and incoherent interfaces. The dynamic failure of modern composite and layered materials and the phenomenon of earthquake rupture growth along geological faults have motivated these studies.
- *Aeronautical Engineering and Propulsion.* Research in the aeronautical engineering area includes studies of airplane trailing vortices and separated flows at high angles of attack. Research work in the propulsion area has centered on the fluid dynamic problems associated with combustion, solid propellant rocket motor instabilities, fluid dynamics and optimization of scramjets, and pulse detonation engines.

- *Biomechanics of Fluids and Solids.* The kinematics and dynamics of fluid flows in biological systems are studied in experiments, numerical simulations, and theoretical analyses. These flows are often characterized by unsteady vortex dynamics, coupled fluid interactions with flexible material surfaces, non-Newtonian fluid behavior, and, in some cases, compressibility. Areas of active research include animal swimming and flying, cardiovascular fluid dynamics and hemodynamics, the mechanics of morphing/ active deformable surfaces for flow control, and biologically inspired design of engineering systems.
- *Technical Fluid Mechanics*. These areas are related to a variety of modern technological problems and, in addition, to the traditional aeronautical problems of drag, wing stall, and shear flow mixing. Additional areas of activity include bluff-body aerodynamics, fluid-structure interaction, turbulent combustion, laminar diffusion flames and their instabilities, explosions, hydrodynamics and two-phase flows, interaction of vorticity with free-surface, cardiac flows, swimming and flying, and active and passive control of transition and turbulence. Acoustics problems studied include jet noise, combustion noise, and instabilities such as the generation of organ pipe oscillations in large burners of electric generating plants.
- *Fluid Mechanics, Control, and Materials.* The effects of boundary conditions on turbulence characteristics and general flow physics, scaling and controllability are investigated using interdisciplinary methods based on developments in materials science and control techniques. Experimental manipulation of canonical and simple model flows is used to probe fundamental issues of flow physics and control.

Physical Facilities

The Graduate Aerospace Laboratories contain a diversity of experimental facilities in support of the programs described above. The Cann Laboratory is a teaching facility utilized for graduate and undergraduate experiments in fluid and solid mechanics. Low-speed wind tunnels include the John W. Lucas Adaptive Wall Tunnel, the Merrill Wind Tunnel, which can be operated by a single person, and special-purpose flow facilities. Both a high-speed water tunnel (100 feet per second) and a free-surface water tunnel are housed in the hydrodynamics laboratory; they are used for studies of acoustics, laminar-turbulent flow transition, and the structure of turbulent shear flows. Smaller water channels and a tow tank for studies of wave motion and flow visualization are also available. For investigations of high-speed flows, there is a Ludwieg tube, a supersonic shear layer facility, a hypervelocity expansion tube, and the T5 shock tunnel for studying hypervelocity gas flows up to 7 km/s. Shock tubes and other special facilities are available for the study of extreme temperatures, shock waves, deflagrations, detonations acoustics, and combustion at variable pressure conditions. A 40-meter tilting water flume and wave generation facility is available for studies of small-scale, self-propelled vehicle prototypes, fluid dynamic energy conversion, and environmental flow studies.

The solid and structural mechanics laboratories contain standard as well as special testing facilities for research related to aircraft, deployable space structures, and failure/fracture behavior of materials under static and dynamic loads, including three servo-hydraulic facilities, two of which operate on a "tension/torsion" mode, and a nanoindenter. A range of digital and film high-speed cameras offering recording at rates up to 100 million frames per second are available for the study of fast phenomena, such as wave propagation, hypervelocity impact, and the mechanics of static and dynamic fracture. Dynamic testing facilities include specialized electromagnetic loading devices (stored energy ~120 kJ), a drop weight tower, split Hopkinson bars (axial/torsional), and plate impact apparatus. Diagnostic devices include full-field interferometric and high-speed temperature measurements, both for static and dynamic applications. Other specialized facilities include a Class One clean room area that houses microelectronic wafer inspection metrology tools, and the Small Particle Hypervelocity Impact Range (SPHIR) jointly operated with JPL, which is capable of launching micrometeoroid surrogate particles at speeds up to 8 km/s. Facilities are available for scanning microscopy (AFM, STM) and electromechanical characterization of materials.

State-of-the-art electronic instrumentation is being developed and used. Extensive use is made of computer systems for real-time control of experiments, for data acquisition, processing, and storage, and for digital image processing. Computational facilities include powerful workstations, on-campus high-performance computing machines, and remote supercomputers such as those generally available at NSF, NASA, and DOE centers. Graphics workstations are available to support research in computational fluid dynamics and solid mechanics.

APPLIED AND COMPUTATIONAL MATHEMATICS

An interdisciplinary program of study in applied and computational mathematics that leads to the Ph.D. degree is offered by the Computing & Mathematical Sciences department. In addition to various basic and advanced courses taught by the applied and computational mathematics faculty, broad selections are available in mathematics, physics, engineering, and other areas. Students are expected to become proficient in some special physical or nonmathematical field. A subject minor in applied computation is offered jointly with the computer science option.

In addition to the applied and computational mathematics faculty, professors from other disciplines such as mathematics, physics, engineering, and biology supervise research and offer courses of special interest. The applied and computational mathematics group has access to supercomputers and concurrent computers. Library facilities are excellent, comprising all the journals, a complete general library, and a special research library in engineering and applied science.

The present graduate program is one leading mainly to the Ph.D. degree. The curriculum consists of two types of courses: those that survey the methods used in applied and computational mathematics, and those that have a special applied and computational mathematics flavor and represent active research interests of the members of the faculty. Among the latter have been wave motion, perturbation theory, fluid mechanics, optimization, stochastic processes, wavelet analysis, signal processing, numerical analysis, computational electromagnetism, and computational fluid dynamics. Through study outside of applied and computational mathematics, each student is expected to become competent in some special physical or nonmathematical field. In this way, subjects for research appear naturally, and a broad educational program is provided.

The group primarily interested in applied and computational mathematics currently consists of approximately 25 students and eight professors. Also, each year many distinguished visitors come either to present lectures or remain in residence for large parts of the academic year.

Areas of Research

Research is particularly strong in theoretical and computational fluid mechanics, theoretical and computational materials science, computational electromagnetism, numerical analysis, ordinary and partial differential equations, multi-scale analysis, geometric integration, integral equations, linear and nonlinear wave propagation, water waves, bifurcation theory, perturbation and asymptotic methods, stability theory, variational methods, approximation theory, uncertainty quantification, randomized algorithms, optimization, statistical estimation, computational harmonic analysis, stochastic processes, signal and imaging processing, inverse problems, mathematical biology, large-scale scientific computing, and related branches of analysis.

APPLIED MECHANICS

Areas of Research

Advanced instruction and research leading to degrees of Master of Science and Doctor of Philosophy in applied mechanics are offered in such fields as elasticity; plasticity; wave propagation in solid media; mechanics of quasi-static and dynamic fracture; dynamics and vibrations; finite element analysis; and stability, control, and system identification of mechanical and structural systems. Research studies in these areas that illustrate current interests include linear and nonlinear random vibrations of uncertain dynamical systems; structural dynamics and control for earthquake and wind loads; linear and nonlinear problems in static and dynamic elasticity, plasticity, and viscoelasticity; computational mechanics; mechanics of time-dependent fracture;

chaotic behavior of dynamical systems; and material instabilities and phase transformations in solids.

Physical Facilities

In addition to the regular facilities in the Division of Engineering and Applied Science, which include extensive computing facilities, certain special facilities have been developed in connection with applied mechanics activities. The vibration laboratory is equipped with a good selection of modern laboratory apparatus and instrumentation for experimental research in shock and vibration, and the earthquake engineering research laboratory contains specialized equipment for vibration tests of buildings, dams, and other structures, and for the recording and analysis of strong-motion earthquakes. The solid mechanics laboratory located in the Graduate Aeronautical Laboratories contains extensive testing equipment for the study of fracture and structural failure. Excellent computing facilities are available through the campus computing network and in the specialized centers of various research groups.

APPLIED PHYSICS

The Applied Physics option was instituted in 1970 in order to provide an interdivisional program for undergraduate and graduate students at Caltech interested in the study of both pure and applied physics. The small size of Caltech, coupled with its strength in the basic sciences and engineering, has made it possible for faculty and students alike to pursue wide-ranging interests in the application of modern physics to the development of new technology. Research efforts in applied physics are driven by a fundamental understanding of the physical principles underlying applications and a strong motivation to use this knowledge to invent new experimental techniques, processes, devices and materials. Core and affiliate faculty spanning several divisions on campus participate in instruction and research leading to B.S., M.S., and Ph.D. degrees in applied physics.

This program is designed for undergraduate and graduate students who wish to expand their training beyond the study of fundamental physics to include research and development of real-world applications. The training helps develop a solid foundation in physics through introductory courses in classical physics, classical electrodynamics, quantum mechanics, thermodynamics, statistical mechanics, and mathematical physics. More advanced training is provided through course work and research activites in solid state physics, electromagnetic wave propagation, opto-electronic materials and devices, transport phenomena in hydrodynamic and condensed matter systems, plasma physics, biological physics, semiconductor principles and devices, quantum electronics, and low dimensional electronic systems.

Students are encouraged early on to develop strong experimental skills for advanced laboratory work, including familiarity with numerical computation for data and image analysis and software packages for instrument automation. There exist many learning opportunities along these lines, from courses in microfabrication and laboratory work to independent research opportunities with various research groups. Undergraduate students are encourages to explore and will find numerous opportunities for developing their research interests into junior or senior thesis projects leading to publication.

Physical Facilities

Research in applied physics covers a broad spectrum of activities distributed across campus. Instructional and research activities of the core faculty are housed in the Thomas J. Watson, Sr., Laboratories of Applied Physics, a 40,000-square-foot building with state-of-the-art research laboratories, a central microfabrication facility, faculty and student offices, and a conference room and instructional classroom, all nestled around a beautiful courtyard with a fountain pool.

Additional research laboratories and faculty and student offices are located in the Harry G. Steele Laboratory of Electrical Sciences, built in 1965 with funds from the Harry G. Steele Foundation and the National Science Foundation. The building, which is connected by an overhead bridge to the Watson Laboratories, conveniently also houses the Kavli Nanoscience Institute.

ASTROPHYSICS

Caltech is one of the world's preeminent centers of astronomical research. This is due to the combination of excellent human resources with premier observational facilities and computational infrastructure. Fundamental discoveries in astronomy and astrophysics are a part of Caltech's past, present, and future.

Students from either the astronomy or the physics options are best prepared to undertake research with faculty in the Cahill Center for Astronomy and Astrophysics. Students from related options such as planetary science, computer science, applied physics, and electrical engineering are also welcome.

Areas of Research

Astronomy and astrophysics are synonymous at Caltech. Caltech scientists and students are involved in many frontier areas of research, and have been known to open new ones. Research techniques include observations, theory, numerical simulation, laboratory astrophysics, and detector development. Projects and groups often bridge between these areas of inquiry.

Topics of current research interest include: observational cosmology and the nature of dark matter and dark energy; studies of the cosmic microwave background; galaxy formation and evolution; quasars and other active galactic nuclei and radio sources; studies of the dynamics and composition of galaxies and clusters; physics and evolution of the intergalactic medium; interstellar matter; local star and planet formation; extrasolar planetary systems; the structure of the Galaxy; globular clusters; stellar abundances; supernovae, gamma-ray bursts, and other types of cosmic explosions and transient phenomena; neutron stars and black holes; accretion disks; digital sky surveys and virtual observatory; numerical general relativity; and many others.

Research in planetary and Solar system astronomy is often pursued in cooperation with groups in the Division of Geological and Planetary Sciences. New types of astronomical detectors and satellites, that can revolutionize various areas of astronomical research, are developed with groups in physics and colleagues at JPL.

In addition to maintaining a leading numerical general relativity group, Caltech theorists also use high-performance computing facilities for simulations of supernova explosions, merging black holes, cosmic structure formation, etc. Caltech is leading the development of novel tools for knowledge discovery in massive and complex astronomical data sets, many obtained with Caltech facilities.

History and Current Science at Observational Facilities

Observational astronomy is pursued both from the ground-based sites and from space-based platforms.

Caltech operates, or has access to an unprecedented, comprehensive set of observational facilities, spanning the entire electromagnetic spectrum. Caltech is also playing a key role in opening a new window on the universe, the gravitational wave sky.

Historically, Caltech's pioneering role in astronomy started with Palomar Observatory (about 190 km from campus), funded by the Rockefeller Foundation. The first telescope on the mountain was an 18-inch Schmidt telescope built by Fritz Zwicky, and used to conduct pioneering sky surveys for supernovae, potential planetary hazard asteroids, etc. The 200-inch Hale Telescope, constructed through 1930's and 1940's, has been used to make many historical, fundamental discoveries ever since its commissioning in 1948, including the discovery of quasars, and many studies of stellar populations, galaxies, intergalactic medium, etc., and it continues to produce excellent science. Novel detectors and instruments were developed there, e.g., the first astronomical CCDs and infrared detectors. It is now used for pioneering advances in adaptive optics in addition to optical and infrared spectroscopy. The 48-inch Samuel Oschin Telescope has made possible complete surveys of the northern sky, initially with photographic plates (including the historic POSS-I and POSS-II surveys), and now with large-format CCD array cameras. It is currently operating a uniquely wide field, high-cadence program, the Palomar Transient Factory (iPTF). A much larger camera for this telescope, with a 47 square degree field, will begin operation in 2017, as the Zwicky Transient Factory (ZTF). The 60-inch telescope has been roboticized, and is used to monitor sources discovered by iPTF with innovative instruments including a robotic laser adaptive optics system (Robo-AO). Caltech also operates an 84-inch telescope on Kitt Peak, including a Robo-AO system, as part of the Transient Factory.

In the 1990's, funded mainly by the Keck Foundation, Caltech and University of California constructed two 10-m telescopes on Mauna Kea, Hawaii. The W. M. Keck Observatory produced many recent discoveries in the fields of galaxy formation and evolution, intergalactic medium, extrasolar planets, cosmic gamma-ray bursts, etc. Caltech is a founding partner in the development of the Thirty-Meter Telescope (TMT), the first of the next generation of extremely large optical/infrared telescopes.

At meter to centimeter wavelengths, Caltech operates the Owens Valley Radio Observatory (OVRO) in a radio-quiet location about 400 km from Pasadena, near Big Pine, California. Its facilities include a 40-meter telescope, a new 256 element long wavelength array which can image the entire sky every second, and a 6.1 meter telescope dedicated to observatations of polarized radio emission from the galaxy. New radio and submm telescopes are in design and construction phases. From the 1980s until 2015, Caltech also operated the Caltech 10-m Submillimeter Observatory (CSO) on Mauna Kea in Hawaii, and a series of millimeter interferometers, culminating in the 23-antenna Combined Array for Research in Millimeter-wave Astronomy (CARMA) in the Inyo Mountains. These telescopes pioneered submm imaging and interferometry and mm wave interferometry, now carried out by the international Atacama Large Millimeter/submm Array (ALMA).

In Antarctica, Caltech's BICEP2 telescope, which measures the imprint of inflation's gravitational waves on the COSMIC microwave background, has been expanded and renamed the Keck Array.

On the space observations front, Caltech hosts NASA's Spitzer Science Center (SSC) and Infrared Processing and Analysis Center (IPAC), which are principal national archives for astronomy. Caltech scientists lead or actively participate in a number of astrophysics missions, currently including the Spitzer Space Telescope, and the NuSTAR hard X-ray mission. There are also close connections with Jet Propulsion Laboratory (JPL), that designs and operates a number of NASA's scientific missions. Finally, Caltech astronomers are major users of NASA's astronomical satellites, the Hubble Space Telescope, Chandra, Fermi, Herschel, Planck, etc., ALMA and the NSF's Jansky Very Large Array (JVLA).

Caltech is the headquarters for LIGO lab, which built and operates the world's most sensitive gravitational wave observatory, the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO). Exciting new discoveries are expected as it opens this new window on the universe beginning in 2015.

BEHAVIORAL AND SOCIAL NEUROSCIENCE

The Institute offers an interdisciplinary program of study in neuroscience, psychology, economics, and political science that leads to the Ph.D. degree. The program seeks to train students to do interdisciplinary work at the intersection of the natural and social sciences. At present, members from the biology, computation and neural systems, social sciences, and humanities groups participate in research and training in this area.

Areas of Research
This program is characterized by interdisciplinary research at the frontier of neuroscience, psychology, economics, and political science. Examples of research topics of interest include the following:

- Computational and neurobiological foundations of simple decision making in animals and humans.
- Computational and neurobiological basis of economic and political decision making.
- Affective neuroscience.
- Neurobiological basis of social behavior in human and animal models.
- Neurobiological basis of moral judgment and decision making.
- Applications of neuroscience to economics and political science.

Physical Facilities
Research in this area is carried out in multiple laboratories spanning a wide range of experimental techniques—from behavioral experiments to single unit neurophysiology. Researchers also have access to two state-of-the-art facilities: the Caltech Brain Imaging Center, which contains various human and animal brain scanners, and the Social Science Experimental Laboratory, which contains state-of-the-art facilities for conducting behavioral economic experiments of group and market interactions.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

Biochemistry and molecular biophysics has been established as an interdisciplinary program, at the interface of biology, chemistry, and physics, that seeks to understand the chemistry of life. Thus, biochemists and molecular biophysicists study the atomic structure and folding of biopolymers; their interactions with each other and with small molecules; and the roles of particular biopolymers and biopolymer assemblies in cellular physiology. The basic building block of life is the cell; the intellectual focus of modern biochemistry and molecular biophysics is to understand how individual parts interact to give cells their wide spectrum of functions. In particular, biochemistry and molecular biophysics addresses the principles through which the individual components of cells combine in an orderly self-association to produce their form, their function, and their dynamic behavior.

Areas of Research
General areas of research represented within the option include signal transduction, cell cycle, DNA and RNA structure and metabolism,

control of gene transcription during development, electron transport proteins and bioenergetics, biological catalysis, macromolecular structure, membrane proteins, and biotechnology and biomolecular engineering. More specific examples of biological phenomena currently under study include the transduction of signals received by cell surface receptors into an appropriate response, as in chemotaxis or transmission of signals across synapses in the nervous system; the replication of DNA; the biochemical networks that control initiation and termination of cell division; the controlled transcription of DNA sequences in the genome into RNA and the processing of this RNA into mRNA and the subsequent translation into protein; the molecular mechanisms controlling the differentiation of precursor cells into specialized cells such as neurons, lymphocytes, and muscle cells; the mechanisms by which synaptic transmission in the brain is regulated during thinking and the formation of memories; the processes, driven by fundamental principles of chemical bonding and molecular energetics, by which a given linear sequence of amino acids folds into a specific three-dimensional structure in the appropriate cellular environment; how electrons move within a cell to accomplish the many redox reactions necessary for life; how light is harvested by photo-pigments and is perceived in vision; the function of integral membrane proteins in energy and signal transduction processes; and the mechanisms by which enzymes both efficiently and specifically catalyze biochemical interconversions. This fundamental understanding of the molecular basis of biological processes provides a powerful base for the development of applications in medicine, including biotechnology and rational drug design, and in the chemical industry, where nucleic acids, proteins, and their analogs are now being used in the development of chemical systems for novel applications, and where mutagenesis and selection systems are used to produce novel materials.

BIOENGINEERING

Bioengineering research at Caltech focuses on the application of engineering principles to the design, analysis, construction, and manipulation of biological systems, and on the discovery and application of new engineering principles inspired by the properties of biological systems.

Areas of Research

- *Bioimaging* (Cai, Dickinson, Gharib, Lester, Meyerowitz, Pierce, Shapiro, Yang)

  Biophotonics, advanced imaging technologies, computational image analysis, noninvasive biomedical imaging, single-molecule technologies, flow-field imaging technologies, in situ amplification.

- *Bioinspired Design* (Dabiri, Gharib, Greer, Hajimiri, Ismagilov, Murray, Shapiro, Tirrell, Winfree)

  Engineering physiological machines, engineering self-powered technologies, control systems, synthetic heteropolymers, and self healing circuits and systems.

- *Biomechanics* (Bhattacharya, Dabiri, Dickinson, Gharib, Greer, Meyerowitz, Phillips, Roukes)
  Molecular and cellular biophysics, cardiovascular mechanics, muscle and membrane mechanics, physiology and mechanics offlapping flight, multicellular morphodynamics, cell-biomaterial interactions.

- *Biomedical Devices* (Burdick, Dabiri, Emami, Gharib, Hajimiri, Heath, Ismagilov, Meister, Roukes, Shapiro, Siapas, Tai, Yang)
  BioNEMS, BioMEMS, laboratories-on-a-chip including microfluidic systems, neural networks, microscopes and diagnostics, novel measurement principles, neural interfaces and prostheses, locomotion rehabilitation, molecular imaging during surgery.

- *Cell and Tissue Engineering* (Arnold, Elowitz, Gharib, Gradinaru, Ismagilov, Shapiro, Tirrell)
  Multicellular morphodynamics, principles of feedback between tissue mechanics and genetic expression, non-natural protein biomaterials, cell-biomaterial interactions, developmental patterning.

- *Molecular Medicine* (Baltimore, Bjorkman, Davis, Deshaies, Gradinaru, Hay, Ismagilov, Lester, Mazmanian, Pierce)
  Engineering immunity, cancer vaccines, AIDS vaccine, novel anti-cancer therapeutics, Parkinson's disease, schizophrenia, Huntington's disease, nicotine addiction, microbiome perturbations in disease, molecular basis of autism, programmable chemotherapies, conditional chemotherapies, nanoparticle drug delivery.

- *Molecular Programming* (Aravin, Murray, Pierce, Qian, Rothemund, Winfree)
  Abstractions, languages, algorithms, and compilers for programming nucleic acid function, molecular information processing, molecular complexity theory, free-energy landscapes, metastable systems, self-assembly across length scales, algorithmic self-assembly, synthetic molecular motors, in vitro and in vivo nucleic acid circuits.

- *Synthetic Biology* (Aravin, Arnold, Elowitz, Gradinaru, Ismagilov, Murray, Pierce, Qian, Rothemund, Shapiro, Tirrell, Winfree)
  Principles of biological circuit design, genetic circuits, protein engineering, noncanonical amino acids, nucleic acid engineering, rational design, directed evolution, metabolic engineering, biofuels, biocatalysts, elucidation of systems biology principles using synthetic systems.

• *Systems Biology* (Aravin, Cai, Doyle, Elowitz, Goentoro, Heath, Ismagilov, Lester, Meister, Meyerowitz, Murray, Phillips, Sternberg, Winfree)
Roles of circuit architecture and stochasticity in cellular decision making, feedback, control, and complexity in biological networks, multicellular morphodynamics, principles of developmental circuitry including signal integration and coordination, spatial patterning and organ formation, principles of feedback between tissue mechanics and genetic expression, neural development, and disease.

BIOLOGY

Recent dramatic progress in our understanding of the nature of life has revolutionized the science of biology. Applications of the methods, concepts, and approaches of modern mathematics, physics, chemistry, and information science are providing deep insight into basic biological problems such as the manner in which genes and viruses replicate themselves; the control of gene expression in cells; the regulation of cellular activity; the mechanisms of growth and development; and the nature and interactions of nerve activity, brain function, and behavior. Qualified experimental and computational biologists will find opportunities for challenging work in basic research as well as in medicine and in biotechnology.

Because of the eminent position of the California Institute of Technology in both the physical and biological sciences, students at the Institute have an unusual opportunity to be introduced to modern biology.

Areas of Research

Research (and graduate work leading to the Ph.D. degree) is chiefly in the following fields: biochemistry, biophysics, cell biology, developmental biology, genetics, genomics and computational biology, immunology, microbiology, molecular biology, neurobiology, structural biology, and systems biology. Biochemical methodology plays an important role in many of these fields, and there is extensive interaction with related programs in biochemistry within the Division of Chemistry and Chemical Engineering, including the biochemistry and molecular biophysics option.

The programs in cellular, molecular, and developmental biology are based upon approaches derived from biochemistry, biophysics, and genetics that offer new possibilities for expanded insight into long-standing problems. Neurobiology is a major area of emphasis within the Division of Biology and Biological Engineering. A comprehensive program of research and instruction in neurobiology has been formulated to span from molecular and cellular neurobiology to the study of animal and human behavior, including the computational modeling of neural processes.

A Geobiology option is described in the geological and planetary sciences section.

Physical Facilities
The campus biological laboratories are housed in seven buildings: the William G. Kerckhoff Laboratories of the Biological Sciences, the Gordon A. Alles Laboratory for Molecular Biology, the Norman W. Church Laboratory for Chemical Biology, the Mabel and Arnold of Behavioral Biology, the Braun Laboratories in Memory of Carl F and Winifred H Braun, the Beckman Institute, and the Broad Center for the Biological Sciences. They contain classrooms and undergraduate laboratories, as well as research laboratories where both undergraduate and graduate students work in collaboration with faculty members. Special facilities include rooms for the culturing of mutant types of *Drosophila,* a monoclonal antibody production facility, a fluorescence-activated cell sorter facility, scanning and transmission electron microscopes, a confocal microscope facility, a magnetic resonance imaging center, a transgenic mouse facility, a high throughput sequencing and microarray analysis facility, and a protein expression and purification center.

About 50 miles from Pasadena, in Corona del Mar, is the William G. Kerckhoff Marine Laboratory. This laboratory provides facilities for research in cellular and molecular biology using marine animals, and for collecting and maintaining these animals.

CHEMICAL ENGINEERING

The chemical engineering faculty teach and conduct research on fundamental chemical, biological, and transport processes and their application in understanding, designing, and controlling a broad spectrum of complex chemical, biochemical, and environmental processes. The faculty and students utilize their analytical skills and laboratory resources to study diverse processes and to synthesize new materials. The combination of engineering principles, chemistry, biology, physics, and mathematics that characterizes chemical engineering at Caltech enables students and faculty to contribute to the solution of a wide range of critical problems and to aid in creating new areas of science and technology.

Areas of Research
Many different research areas are offered to students seeking the degrees of Master of Science or Doctor of Philosophy in chemical engineering. Particular research fields emphasized in the department include the following:

- *Biological Design and Engineering.* Engineering of proteins and metabolic pathways by computational and laboratory evolution approaches. Biocatalysis for sustainable "green" production of pharmaceuticals and specialty chemicals. Engineering organisms to convert biomass to fuels and chemicals.
- *Fluid Mechanics and Transport Processes.* Mechanics of polymeric liquids, microstructured fluids, colloidal dispersions and sus-

pensions, and granular media. Transport in heterogeneous media.

- *Polymer Physics and Chemistry.* Molecular understanding of polymer melt rheology. Optical properties of polymer blends. Dynamic modeling of polymer structure and rheology. Synthesis of tailored polymers by chemical and biological means.
- *Biomaterials.* Synthesis and properties of organic materials designed for use in living systems. Therapeutic modification of existing systems.
- *Cellular Engineering.* Quantitative analysis and redesign of molecular events governing cell behavior.
- *Catalysis and Biocatalysis.* Synthesis of molecular sieves and organic-inorganic hybrid materials. Synthesis of inorganic membranes for gas separations and catalysis. Biological routes to the synthesis of chemicals.
- *Complex networks of reactions, cell, and organisms.* Studies of microbial communities in environment and interactions of microbial communities with their human host.
- *Microfluidics.* Science of single molecules, crystals, and cells. Fundamental studies of fluid flow and interfacial phenomena. Applications to diagnostic and therapeutic problems in Global Health.
- *Electronic Materials and Devices.* Plasma processing of semiconductors, pattern etching and deposition. Modeling and simulation of pattern-dependent effects. Chemical reaction dynamics of plasma-surface interactions.
- *Microplasmas.* Sources of reactive radicals and ions at high pressures. Microreactors for gas conversion/pollutant destruction. Synthesis of nanocrystals. VUV-excimer radiation emitters.
- *Nanotechnology.* Aerosol synthesis of nanoparticles for microelectronic and photovoltaic applications. Nanoprobes, nanomechanics, nanofluidics. Crystallization in carbon nanotube cavities. Synthesis and characterization of quantum dots and nanostructural materials. Environmental consequences of nanotechnology.
- *Environmental Chemical Engineering.* Physics and chemistry of atmospheric gases and aerosols, bioaerosols, climate change.
- *Aerosols and Colloids.* Nucleation and growth of particles. Particle formation and reactions. Structure and properties of colloidal dispersions. Aerosol and colloidal particle characterization.
- *Applied Mathematics and Computational Physics.* Supercomputer applications in fluid mechanics and environmental modeling. Concurrent computing. Asymptotic analyses of transport processes.
- *Physics of Complex Fluids.* Structures, phase transitions, and dynamics of polymers, liquid crystals, surfactant solutions, suspensions and active matter.
- *Materials for Energy Technologies.* Electrochemistry of fuel cells. Ion transport through solids. Design of thermoelectric materials.

Physical Facilities
The chemical engineering laboratories, mainly housed in the Eudora Hull Spalding Laboratory of Engineering and the Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering, are well equipped. The facilities include experimental reactors, computational facilities, NMR spectrometers, and numerous special research equipment for molecular simulations, DNA synthesis, and electronic, optical, and chemical measurements.

CHEMISTRY

Caltech offers exciting opportunities for study and research at the frontiers of chemical science. With approximately 30 faculty, the hemistry program provides depth in the traditional areas of chemistry—organic and inorganic chemistry, chemical physics, theoretical chemistry, and chemical biology. Research areas include chemical synthesis and catalysis, chemical dynamics and reaction mechanisms, biochemistry, bioinorganic, bioorganic, and biophysical chemistry, and materials chemistry. Chemical research at Caltech is also highly interdisciplinary, mirroring the increasing importance of molecular understanding in many fields of science. Active interactions exist between chemistry and other disciplines at Caltech, especially applied physics, biology, chemical engineering, environmental science, geological and planetary sciences, and materials science. Major initiatives are fostering broad collaborations in energy and environment, molecular medicine, and nanomaterials.

Teaching is an important component of the chemistry option. Caltech has trained generations of chemists who have become leaders in academia, industry, and government, through undergraduate and graduate programs that are designed to encourage the greatest possible amount of freedom, creativity, and flexibility.

Areas of Research
Caltech has a long and continuing reputation for excellence in fundamental chemistry in molecular structure and the nature of chemical bonding. Much of the current research in chemistry is directed at establishing and manipulating the mechanisms of reactions of fundamental chemical and biological significance.

Programs in chemical physics emphasize studies of molecular dynamics and structure using techniques that include femtosecond lasers, molecular beams, ultra-high sensitivity spectroscopy, and mass spectrometry, while novel methods such as ultrafast electron diffraction and force-detected magnetic resonance are being developed and applied to systems of increasing complexity. Interdisciplinary research includes the development of powerful approaches to fabricate, assemble, and utilize nanometer-scale structures; spectroscopy and fundamental chemical mechanisms of reactions in Earth and planetary atmospheres, star formation, and interstellar chemistry; the dynamics of phase transitions; and novel methods in mass spectrometry.

Catalysis by transition metals represents a central area of research in the inorganic and organometallic areas. Current research interests include the uses of transition metal complexes as homogeneous and heterogeneous catalysts for polymer synthesis, solar energy conversion and storage, and methane and water oxidation. Reactions of molecules on surfaces are an important focus, especially on semiconductors. Research in bioorganic and bioinorganic chemistry includes the chemical basis of synaptic transmission by ion channels; investigations of molecular recognition and sequence-specific ligand binding to DNA; DNA-mediated charge transport; and design of artificial transcription activators.

Chemical synthesis, a key part of much of the research described above, is the primary research goal of several groups, and includes projects aimed at the synthesis of complex organic molecules of importance in biology and human medicine. These efforts include development of new and synthetically useful chemical transformations mediated by novel organic and transition metal-based catalysts. The division has an exceptional program in polymer science, with emphasis on the development of strategies and methodologies for the synthesis of designed polymers using chemical- and biological-based approaches.

The theoretical chemistry program ranges from fundamental studies of electron transfer to excited states and reaction dynamics of small molecules, to simulations of biological systems and materials. In these studies, theoretical techniques are being developed to provide detailed understanding of electron transfer processes, proton transfer reactions, energy randomization processes within molecules, and the dynamics of reacting systems. Computer simulations are addressing ever more complex systems, ranging from metals and superconductors to soft materials and biomolecules.

Research in biochemistry and molecular biology within the chemistry division exists within the larger framework of biochemical studies at Caltech, and includes crystallographic and spectroscopic analyses of macromolecule structures; studies on the design, folding, and stability of macromolecules; the mechanisms of enzyme catalysis and allosteric transitions; interactions between proteins and nucleic acids; macromolecular assemblies mediating replication, transcription, and protein biosynthesis; the mechanism and functional role of protein glycosylation; and mechanisms of ion and electron transport in biological membranes.

Physical Facilities

The laboratories of chemistry consist of eight units providing space for about 25 research groups, including 300 graduate students and postdoctoral research fellows. Crellin and Gates laboratories house several research groups, the divisional instrumentation facilities, and the divisional administrative offices. Synthetic research groups occupy the Arnold and Mabel Beckman Laboratory of Chemical Synthesis and Church laboratories. The Braun Laboratories and the Broad Center for the Biological Sciences house biochemical groups and are shared with the

Division of Biology and Biological Engineering. The Arthur Amos Noyes Laboratory of Chemical Physics is one of the major research facilities for chemical physics and inorganic chemistry and is adjoined by the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory. Chemistry groups recently joined several chemical engineering colleagues in the new Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering. A number of resource centers serving researchers of the division are located in the Beckman Institute.

CIVIL ENGINEERING

Civil engineering includes the research, development, planning, design, and construction associated with the infrastructure of the built environment. Dealing with the function and safety of such facilities as buildings, bridges, pipelines, dams, power plants, and harbors, it is concerned with the protection of the public against natural hazards such as earthquakes, winds, floods, landslides, water waves, and fires.

Recent advances in technology, the escalation of urban problems, and the exploration of space have broadened the applications of civil engineering, increasing the scope of research. New problems have presented special challenges to the civil engineer well-trained in the fundamentals of his or her profession. For this reason, in the advanced study of civil engineering at the Institute, the application of fundamental scientific principles and mathematics is emphasized for the solution of engineering problems.

Areas of Research

Graduate work leading to advanced degrees lies chiefly in the following fields: structural engineering and structural dynamics; earthquake engineering; applied mechanics; geotechnical engineering; aerospace structures; and environmental engineering (see also environmental science and engineering). In the past few years, graduate students and members of the faculty have pursued a variety of research programs, including the analysis of structures subjected to earthquakes and other dynamic loadings; optimal performance-based structural design; system identification and control of structures; structural health monitoring; the use of finite element methods for structural analysis; seismic risk and structural reliability; earthquake early warning systems; mechanics of soil and other granular materials; and mechanics of space structures. Students whose interests are in environmental problems may enroll for graduate degrees in either civil engineering or environmental science and engineering.

Physical Facilities

Civil engineering activities are housed in two buildings: the Gates-Thomas Laboratory, which contains the earthquake engineering research laboratory and the vibration laboratory; and the W. M. Keck

Engineering Laboratories, which contains the environmental science and engineering laboratories. Excellent computing facilities are available through the campus computing network and in the specialized computing centers of various research groups. Seismic instrumentation networks include the Southern California Seismic Network and the Community Seismic Network.

COMPUTATION AND NEURAL SYSTEMS

What does the brain compute? How does it do it? And why? Faculty and students in the CNS option study how information is acquired and processed by the brain. They are also interested in designing machines that are adaptable, intelligent, and autonomous. The unifying theme of the program is the study of the relationship between the physical structure of a computational system (synthetic or natural hardware), the dynamics of its operation and its interaction with the environment, and the computations that it carries out.

Areas of interest include coding and computation in networks of neurons, sensory systems (vision, audition, olfaction), learning and memory, control and motor behavior, and planning and decision making. Thus, CNS is an interdisciplinary option that benefits from, and integrates, multiple traditional areas of expertise: molecular, cellular, neural, and systems biology, electrical and mechanical engineering, computer science, psychology, and cognition, applied mathematics, and physics.

Faculty in the program belong to the Division of Biology and Biological Engineering, Division of Engineering and Applied Science, Division of Physics, Mathematics and Astronomy, and Division of the Humanities and Social Sciences. They have an interest in developing conceptual frameworks and analytical approaches for tackling seemingly disparate problems that share a common deep structure at the computational level. Students in the program will partake of a wide-ranging curriculum that will promote a broad understanding of neurobiology, sensory psychology, cognitive science, computational hardware and software, and information theory.

Areas of Research

Areas of research include the neuron as a computational device; the theory of collective neural circuits for biological and machine computations; algorithms and architectures that enable efficient fault-tolerant parallel and distributed computing; learning theory and systems, pattern recognition, information theory, and computational complexity; computational modeling and analysis of information processing in biochemical and neural networks; the design and use of synthetic macromolecules as computational devices; light and magnetic resonance imaging of cell lineages, cell migrations, and axonal connections in the forming nervous system; learning, plasticity, and memory; experimental and modeling studies of localization and recognition by sensory systems (vision, olfaction, audition) in insects and vertebrates on the basis of electrophysiology, psychophysics, and functional imaging techniques; multiunit recordings in behaving animals; neuroprosthetic devices and recording methods in animals and humans; imaging and stimulation of cortical areas in humans and other primates using functional MRI, TMS, and tDCS; decision making, attention, awareness, emotion, and consciousness in the primate brain using a combination of neurophysiological, psychophysical, and computer modeling techniques; cognitive psychology; and the study of evolution in natural and artificial systems.

COMPUTER SCIENCE

Although computing is a ubiquitous tool in all areas of study and research at Caltech, computer science focuses on the theory and technology of computation itself: it is truly the study of information, and of the structures that communicate, store, and process information. Whether these structures are expressed in hardware and called machines, in software and called programs, or in nature or society, the fundamental concepts are similar. Students of the computer science option within the Computing & Mathematical Sciences department at Caltech do not specialize along traditional lines that divide hardware and software, systems and applications, or theory and experiment. Rather, a unified approach to the design and analysis of computing structures is taken both in courses and in research.

Unlike the study of physical and natural sciences, the objects of study by computer scientists are artificial systems; that is, structures that are purposefully designed, taking into account physical limitations of the real world and fundamental requirements of the computation itself. Thus, design assumes a role equal in importance to analysis and is a term found frequently in the curriculum and research. Design is not only a creative activity but is also formal and systematic. Managing the great complexity of useful systems requires a representation of computations amenable to both mathematical treatment and implementation.

Areas of Research

Research and advanced courses leading to the Ph.D. degree in computer science are concentrated in the following areas: VLSI systems; quantum and molecular computation; computer architecture; parallel and distributed computation; theory of computation; information theory; machine learning and computational finance; computer vision; computer graphics; discrete differential geometry; computer-aided design; and networking. Research projects frequently involve work in several of these areas, with both theoretical and experimental aspects, as well as connections with such fields as mathematics, physics, biology, economics, and electrical engineering. Crosscutting themes include:

- *Physical Implementation of Computations.* Computations must ultimately be implemented in some physical medium (e.g., semiconductor electronics, DNA self-assembly, quantum states of elementary particles, molecular electronics). Developing robust disciplines, abstractions, and methodologies that allow the design of reliable computing substrates has been a focus of the option since its inception. Caltech has been a leader in the early development, engineering, and design of very large scale integrated (VLSI) circuits. Beyond VLSI, efforts are under way to understand quantum, biomolecular, and molecular electronic substrates as possible media for future computing machines. As was the case with semiconductor electronics, Caltech computing can draw on the world-class expertise of its biology, physics, and chemistry departments as it tackles the many challenging opportunities that these new substrates present.

- *Systematic Design*. A key theme in the Caltech computer science option is the systematic design of systems at all levels. This theme shows up in the design of numerical algorithms for physical simulation and computer graphics, design of concurrent and distributed systems, abstractions for physical computing substrates, design of learning systems, design of programming languages, automated optimization of computations for both software and hardware implementation, as well as control and optimization of networks. The success of computer systems has allowed the building of systems of unprecedented scale and complexity. These systems can only be understood and managed if we carefully contain the complexity involved. We can only hope to create and optimize efficient computing artifacts by systematically defining and exploring their design space. This does not say that system design is not a creative endeavor, but rather that careful design allows us to expose the places where creativity is most needed, and to carefully assess the impact of new ideas and techniques.
- *Concurrency.* The physical world is highly parallel. Caltech computer science has embraced concurrency as a fundamental feature of computing systems from its inception. Within the option, parallelism is a theme at all levels, from physical circuits through tightly coupled, concurrent multiprocessors, through distributed systems, up to Internet-wide computing systems and beyond. Disciplines and systematic design for defining and managing the potentially complex interactions in parallel systems is a key focus.
- *Robust Modeling of Physical Systems*. Caltech computer science also has a unique focus in developing rigorous and robust models of the physical world. These models are mathematically and physically sound, often derived from differential geometric principles, and serve as a basis for computer graphics and vision research, as well as the simulation of mechanical, optical, and biological systems.
- *Theory*. A key component of systematic design is a strong theoretical understanding, which provides a basis for synthesis, analysis, and verification. The theory of computation focuses on deep mathematical problems, many of which have substantial

technological impact. Theory is not relegated to a single group at Caltech, but rather forms an integral part of all disciplines. As such, it has a strong connection to actual practice in each domain. Theory in computer science at Caltech also includes traditional areas such as complexity algorithms, theories of numerical computation, optimization, probability, and game theory.

- *Interdisciplinary Research.* Computation enables better control and understanding of the physical world—two ubiquitous themes at Caltech. Computer simulations, modeling, and analysis are now key enablers, allowing all fields of science to advance rapidly. Modern mechanical and aeronautical systems are enabled by vast computational processing for sensing and control. Furthermore, insights into computational management of information helps us understand information processing issues in natural systems (e.g., cells and neurons) and build hypothetical models that advance our understanding of natural cognition. Economic analyses play an important role in the design of computing systems and, in addition, research on information systems impacts business and economics. These relations provide many opportunities for scholars in computer science to work closely with colleagues throughout Caltech. The Information Science and Technology (IST) initiative facilitates and promotes such interdisciplinary research (see http://www.ist.caltech.edu).

Physical Facilities

The computer science option has excellent computing facilities ranging from high-performance workstations to multiprocessors and supercomputers. The Computing & Mathematical Sciences department maintains a large computer lab open to students and offers a large collection of software for a wide range of applications. Students have easy access to state-of-the-art equipment. The Institute lib-raries maintain a large collection of journals in computer science and related fields.

COMPUTING AND MATHEMATICAL SCIENCES

Data-driven modeling is becoming increasingly critical in diverse application domains such as machine learning, vision, control systems, biological and engineered networks, neuroscience, economics, and privacy, as well as in many areas of the physical sciences, including high energy physics, earthquake modeling, astronomy, and exploration geophysics. There is enormous potential for research on data-intensive activity of this type, which is highlighted by the emergence of new fields such as “Big Data”, “Decision Science”, and “Network Science.” However, the theoretical foundations of these subjects remain underdeveloped, limiting our understanding and development.

The mission of the CMS graduate program is to address this need by exploring and developing the fundamental mathematical, computational, and economic tools necessary to advance data-intensive science and engineering. That is, we aim to forge the algorithmic foundations necessary to move from data, to information, to action. Key to this mission is a core focus on "algorithmic thinking". Algorithms are not just the basis for advanced technology, they are intrinsic components of diverse fields such as biology, physics, and economics. Studying the structures and mechanisms that communicate, store, and process information from this viewpoint -- whether these structures are expressed in hardware and called machines, in software and called programs, in abstract notation and called mathematics, or in nature and society and called biological or social networks and markets -- is crucial to pushing scientific boundaries. Simply put, it is almost impossible to do research in any scientific or engineering discipline without the ability to think algorithmically.

Because of the diversity of fields where algorithmic thinking is fundamental, there are broad differences in how algorithms are formalized, applied, and studied across areas. Over the years, these differences have been codified and the "language of algorithms" is actually quite distinct across, e.g., computer science, applied math, and electrical engineering. However, a broad view of algorithmic thinking is crucial to scientific breakthrough; and the goal of this program is to train scholars to have an interdisciplinary, cross-cutting view of algorithms.

Faculty and students in CMS are active in a broad array of research areas. Some of these include algorithms, complexity, algorithmic economics, feedback and control, inference and statistics, information systems, machine learning, networked systems, vision, optimization, quantum information, scientific computing, and uncertainty quantification.

CONTROL AND DYNAMICAL SYSTEMS

Some of the most exciting interactions between mathematics and engineering are occurring in the area of analysis and control of uncertain, multivariable, and nonlinear dynamical systems. While changing technology has made control and dynamical systems theory increasingly relevant to a much broader class of problems, the interdisciplinary nature of this area means that it no longer has a natural home exclusively or even primarily within any one of the traditional engineering disciplines. The CDS option, as part of the Computing & Mathematical Sciences department, is designed to meet the challenge of educating students both in the mathematical methods of control and dynamical systems theory and their applications to problems in engineering and science.

Faculty and students in CDS are active in a number of research areas. The primary theoretical areas of research include stochastic and nonlinear dynamical systems, multiscale modeling, optimal and decentralized control, system identification and estimation theory, Bayesian modeling and analysis, uncertainty quantification, and communications and information theory. Active applications include networking and communication systems, embedded systems and formal verification, robotics and autonomy, molecular and systems biology, integrative biology, human physiology, economic and financial systems, computing systems, physics of fluids, quantum mechanics, seismology and earthquake engineering, and space systems.

ELECTRICAL ENGINEERING

Electrical engineering at Caltech emphasizes both electronics and systems. Closely allied with computation and neural systems, applied physics, bioengineering, computer science, and control and dynamical systems, it offers students the opportunity for study and research, both theoretical and experimental, in a wide variety of subjects, including wireless systems, quantum electronics, modern optics, biophotonics, MEMS/NEMS, solid-state materials and devices, power electronics, energy systems, control theory, nanoscale systems, signal processing, data compression, and
communications.

Areas of Research and Physical Facilities
Substantial experimental laboratory facilities, housed mainly in the Moore Laboratory of Engineering, are associated with each of the research fields described on the following pages.

- *Biomedical Micro Implantable Devices* (Choo, Tai,) -- Body tissues (especially neurons), once severely damaged, do not repair or regenerate easily, and often leave behind permanent debilitating deficits. Engineering implant technologies to interface intact tissues and/or to replace defective functions will continue to be the main solutions for many diseases. We research on applying MEMS and nanotechnologies technologies to develop a new generation of micro implants that feature small size and new functionalities. Examples include retinal implant, spinal cord implant, ECG implants, cardiovascular implants, implantable pressure sensors, drug delivery pumps, bio-analyte sensors, etc. Students in this group will need to work extensively in our clean-room facility and collaborate with many other researchers who specialize in biology and/or medicine.
- *Biophotonics* (C. Yang)—Experimental research on imaging and extraction of information from biological targets through the use of light. Current areas of interest include optofluidics, optical phase conjugation, wide field-of-view imaging, chip-scale microscopy, Fourier Ptychographic microscopy and deep tissue optical imaging. More information can be found at http://www.biophot.caltech.edu.

- *Communications and Signal Processing* (Effros, Hassibi, Kostina, Low, Vaidyanathan)—Theoretical and computer experimental work in a wide range of information, communication, and signaling problems. Current research emphases are in network communications, including network capacity bounds, multicasting, distributed operation, network security; access, spectral sharing, dynamic channel allocation, and multiuser detection in wireless systems; multiple-antenna systems and space-time codes; information content and data compression; nonasymptotic information; traffic modeling, routing, congestion control, network architecture, and energy efficiency of computing and information systems; compressive sensing and sparse recovery problems, sparse sensor arrays, multirate digital filters and filter banks, radar signal processing, genomic signal processing, and spectrum sensing. Possibilities exist for joint work with microsystems, wireless communication, digital signal processing, and data compression.
- *Computational Vision* (Perona)—Theory and applications of computer vision. Psychophysics and modeling of the human visual system. Modeling of vision-based decision-making in humans and animals. Current emphasis on visual object recognition; vision-based human-machine interfaces; perception and modeling of human and animal behavior. Areas of collaboration include statistical machine learning, artificial intelligence, neural networks, computer graphics, neurophysiology, psychology, applied probability, robotics, geometry, and signal processing.
- *Control* (Doyle, Hassibi)—Theoretical research is conducted in all aspects of control, with emphasis on robustness, multivariable and nonlinear systems, optimal control, and networks. Theoretical developments are applied to wide variety of areas, including internet, wireless, smartgrid, cell biology, neuroscience, medical physiology, turbulence, wildfire ecology, earthquakes, economics and finance, and foundations of physics.
- *Digital Signal Processing* (Hassibi, Vaidyanathan)—Theoretical and computer-oriented work on a wide variety of problems in digital signal processing. Sparse sensor arrays, sparse signal reconstruction, compressive sensing, array signal processing, multirate digital filters and filter banks, radar signal processing, genomic signal processing, spectrum sensing, digital image processing including half-toning, and other applications."
- *Distributed Information Systems* (Bruck)—Research on synthetic and natural distributed information systems, including information systems in storage and communications (the synthetic part) and the development of abstractions for the analysis and design of biological regulatory networks (the natural part). The information systems work includes developing efficient array codes for increased reliability of RAID storage systems, schemes for representing information in magnetic recording

and optical communications, and methods for representing and protecting information in flash memories. The mathematics of biology-related work includes the development of a calculus for representing computation in gene regulatory networks: for example, demonstrating for the first time that an approximate general computation can be achieved using a finite set of chemical reactions, provided that they operate in a stochastic manner. Past projects include the RAIN (Reliable Array of Independent Nodes) project. The RAIN technology resulted in a spin-off company called Rainfinity (acquired in 2005 by EMC), which focused on software products for the management of network information systems.

- *High-Freqeuncy Integrated Systems* (Hajimiri)—Circuits and system design for communication, sensing, actuation, and control using integrated circuit technology, fully integrated silicon-based millimeter-wave circuits and phased array transceivers, silicon-based THz integrated system, electromagnetically active integrated circuits, novel modulation techniques using integrated electromagnetic structures, high- frequency integrated power generation, equalization for wireline communications, multimode reconfigurable systems, integrated photonics and electronics systems that leverage the strengths of both integrated photonics as well as that of integrated electronics for various applications such as laser line-width control, photonics phased-array, as well as photonics ranging and sensing systems. This area of research also includes analysis and design of communication and sensing building blocks, such as monolithic low-noise amplifiers (LNA), active and passive mixers, local oscillators and frequency synthesizers, frequency dividers and multipliers, power amplifiers, integrated filters, intermediate frequency amplifiers, and baseband digital signal processing. Focus is on innovative engineering solution to high-impact problems in integrated circuits.
- *Integrated Biosensors* (Hajimiri)—Use of intergrated circuits for novel detection techniques of biological matters using various sensing modes (e.g., electrical, magnetic, optical) and leveraging the complexity of silicon-based integrated circuits to create state-of-the-art sensitivity for such sensors for a variety of bio-molecules, such as DNA and proteins. This area also includes analysis of the dynamics and kinetics of such sensors for a variety of applications, including microarrays, point-of-care sensors, and other medical equipment.
- *Integrated Circuits* (Emami, Hajimiri)—Analysis, design, simulation, verification, and testing of integrated circuits for various applications, such as high-speed and wireless communications, wireless local-area networks, highly stable frequency sources, distributed integrated circuit design techniques for ultrahigh speed silicon-based circuits, system and circuit design for multi- band systems, single-chip spectrum analyzers, perfor-

mance limitation of A/D and D/A data converters, and robust circuit- design techniques. Projects also include millimeter-wave silicon-based circuits and arrays, self-healing circuits, high frequency power generation in CMOS, analysis and design of distributed circuits, multimode reconfigurable systems, as well as modeling of the effect of substrate and supply noise in large integrated circuits and design techniques to minimize their effect, examination of integrated passive structures and their fundamental performance limits, and noise modeling in amplifiers, mixers, and oscillators. More information can be found at http://www.chic.caltech.edu and http://www.mics.caltech.edu/

- *Machine Learning and Computational Finance* (Abu-Mostafa)—The Learning Systems Group at Caltech studies the theory, algorithms, and applications of automated learning. The theory of learning uses mathematical and statistical tools to estimate the information (data and hints) needed to learn a given task. The algorithmic aspect of learning deals with the learning mechanisms for different models, and different learning protocols. The applications of learning are very diverse. The group has worked on computational finance applications, where learning is used in financial forecasting, risk analysis, and derivative pricing, as well as other applications in science, commerce, and medicine. There has been a recent emphasis on recommender systems in e-commerce and social networks, as well as profiling applications.
- *MEMS/bioMEMS/OpticalMEMS/NEMS* (Choo, Tai)—We exercise MEMS, Micro- and nano-technologies to build various sensor and actuator devices. Current research projects focus on bioMEMS and microimplant applications, including integrated biochips, microfluidic chips, neuron chips, blood-count chips, neuroprobes, retinal implants and spinal cord implants, wireless ECG, etc. Hands-on fabrication of these devices is specially emphasized for every student in the laboratory at Caltech.
- *Micro-/Nano-technologies* (Choo, Tai) — The micro-/nano-technology research at Caltech focuses on biomedical, electro-mechanical, and optical applications in the micro-/nano-scales. The effort is centered on the two separate clean room facilities -- KNI Lab (http://www.kni.caltech.edu/facilities) for nanoscale research and the Caltech Micromachining Laboratory (http://mems.caltech.edu) for microscale research -- as well as other individual PI's laboratories equipped with state-of-the-art micro-/nanoscale optical/electro-mechanical/bio-medical characterization instruments and powerful computing servers. We exercise MEMS/NEMS, IC, and other nano-scale technologies to develop various sensor and actuator devices. Current research projects focus on bio-MEMS, lab-on-a-chip, heat-assisted magnetic recording (HAMR), next generation on-chip light sources and detectors (nanophotonics), micro-/nano-scale sensing structures for various types of Raman spectroscopy, and energy-harvesting. All aspects of micro-/nano-scale designs,

analysis, and hands-on fabrication are emphasized for every student in this area.

- *Mixed-Signal Engineering* (Emami)—Design and implementation of high-performance analog and digital circuits for wireline and optical data communications, chip-to-chip and on-chip signaling, clock generation and distribution, synchronization, and equalization. Low-power, high-bandwidth analog-to-digital and digital-to-analog converters. Circuits and micro-electronics for biomedical applications such as neural implants, sensing systems and drug delivery. Tools and design methodologies for mixed-signal circuits and systems, with the emphasis on modeling and understanding of the fundamental limits and physical properties.
- *Nanofabrication and Design of Ultrasmall Devices* (Choo, Scherer)—High-resolution lithography and dry etching allow the miniaturization of structures to below 10 nanometers. Using these techniques, ultrasmall optical, magnetic, and fluidic structures can be constructed. Current research includes the design and fabrication of nanocavity lasers; photonic-crystal waveguides and modulators; nanomagnet arrays; nonmechanical oscillators; and microfluidic pumps, valves, and networks on biochips.
- *Networking* (Doyle, Hassibi, Low, Wierman)—Control and optimization of communication and cyber-physical networks such as the Internet and power networks. Current research focuses on fundamental issues in network architecture; network coding, including management and security issues; network storage; and green IT.
- *Network Information Theory* (Effros, Hassibi)—Theoretical analysis and practical design of algorithms for efficiently communicating and storing information in network systems. Current work focuses on the development of computational tools for bounding the performance of large network systems and the derivation of tools for achieving these performance limits in practice. Tools useful to these investigations include information theory, probability theory, graph theory, optimization, and signal processing. Possible areas of collaboration include networking, distributed computing, communications, wireless communications, controls, and digital signal processing.
- *Quantum Electronics and Optical Communication* (Yariv)—Research in this group is addressing the fundamental issues of the interaction of atomic systems and coherent electromagnetic, usually optical, fields and the application of the resulting understanding to demonstrating, in the laboratory, devices and systems central to optical data transmission. Current projects involve slow-light propagation in coupled-resonator systems and semiconductor laser phase control by electronic means, and new generation of swept-frequency lasers for optical radar and imaging. The group is heavily involved in micro- and nano-processing technologies to fabricate the relevant devices. The group has maintained a long tradition of spawning optical communication companies.

- *Smart Grids and Energy Supplies* (Chandy, Doyle, Low, Rutledge, Wierman)—All aspects of energy and power systems, including modeling, analysis, design, and prototyping. Assessment of supplies of oil, gas, and coal, and the implications for alternative energy sources and climate. Control and optimization of networked distributed energy resources, optimal power flow, volt/var control, frequency regulation, renewable integration, PV adoption, data center demand response, electricity market power, storage optimization and EV charging.
- *Wireless Communications* (Hassibi)—Theoretical research on link, system, and network aspects of wireless communications. Current areas of interest include time-varying channel modeling; capacity computations for wireless channels; channel estimation, identification, and equalization; multiple-antenna systems and diversity techniques; space-time codes; modulation techniques; channel access and spectral sharing through various TDMA, FDMA, CDMA, and hybrid techniques; multiuser detection and interference cancellation; dynamic channel allocation; models and performance analysis of wireless networks; ad hoc networks; signal processing for wireless. The research encompasses various areas of information theory, coding theory, stochastic processes, statistical and adaptive signal processing, and network theory.

ENERGY SCIENCE AND TECHNOLOGY

The useful transformation of energy from one form to another drives the engine of civilization. Access to plentiful, inexpensive, and environmentally benign resources would free nations to pursue their greatest human and economic potential. In the modern era, the appetite for energy is convoluted, with a recognition of diminishing fossil fuel resources and of dramatic negative impacts on global climate. The interdisciplinary program in Energy Science and Technology (EST) aims to foster revolutionary methods of harnessing carbon-free energy sources while advancing related technologies in carbon sequestration and further drawing connections to policy and economic considerations. The program brings together traditional topics in thermodynamics and kinetics with modern topics in biomolecular engineering, charge and mass transport, and photoelectrochemistry. Faculty and students in the EST program are drawn from a broad range of academic options, including materials science, chemistry, applied physics, chemical engineering, mechanical engineering, and environmental science and engineering. Areas of emphasis reflect this breadth of disciplines and include photovoltaics, photoelectrochemical cells, bio-fuels, fuel cells, batteries, thermoelectrics, hydrogen generation and storage, and nuclear energy.

ENVIRONMENTAL SCIENCE AND ENGINEERING

Research and teaching in the ESE program span the large scales of global climate variations, the local scales of urban air pollution, and the microscales of microbial ecosystems. Reflecting the interdisciplinary nature of the ESE program, it unites scientists and engineers from Caltech's Division of Geological and Planetary Sciences, Division of Engineering and Applied Science, and Division of Chemistry and Chemical Engineering. Jointly they address, for example, how climate has varied in the past and how it may change in the future, how biogeochemical cycles and chemical reactions control the composition of the atmosphere and local air quality as well as the Earth's global energy balance, and how more efficient and effective ways of producing biofuels or remediating toxic waste can be found. The methods employed in research projects include laboratory studies of fundamental chemical and biological processes; field studies of microbial ecology and of atmospheric chemistry; and computational and theoretical studies of chemical and physical processes on molecular to global scales.

Students enter the ESE program with diverse backgrounds, from the basic sciences of physics, chemistry, and biology to applied science and engineering fields. The curriculum emphasizes interdisciplinary knowledge and is broad, yet it is flexible so that different backgrounds and focus areas can be accommodated.

Areas of Research

- *Atmospheric Chemistry and Air Pollution.* Atmospheric chemistry affects the composition of the atmosphere, properties of clouds, and local air quality. Research areas include cloud chemistry, aerosol chemistry and physics, trace gas photochemistry, and emission sources and transport and reaction pathways of organic species. The methods employed include laboratory studies of aerosol formation and of chemical reactions in the atmosphere; field campaigns with aircraft operated by ESE faculty; satellite missions carried out in collaboration with the Jet Propulsion Laboratory; and theoretical and modeling studies of tropospheric chemistry and the carbon cycle.
- *Environmental Chemistry and Technology.* Environmental chemistry and technology research in ESE addresses fundamental questions in heterogeneous atmospheric chemistry (e.g., chemistry of clouds, fogs, and haze aerosols), in aquatic chemistry, in oxidation and reduction chemistry and technology, in semiconductor photocatalysis, and in hydrogen production from sunlight via electrochemical water splitting.
- *Dynamics of Climate.* Climate dynamics research in ESE addresses fundamental questions about how Earth's climatic features are maintained, how they have varied in the past, and how they may change in the future. Research includes the large-scale dynamics of the atmosphere and oceans, the hydrologic cycle and how it responds to climate changes, monsoon dynam-

ics, and the dynamics of the Southern Ocean, and climates of otherplanets. Methods employed include theoretical and modeling studies, analyses of observational data, and field campaigns to collect oceanographic data.

- *Biogeochemistry and Climates of the Past.* Biogeochemical research in ESE finds application at scales ranging from microbial ecosystems to the global carbon cycle. Current research interests include the marine carbon cycle and its geochemical record in organic matter and carbonate minerals; microbial recycling of nutrients and carbon; and development and use of geochemical proxies for understanding the ancient environment, including its climate.

- *Environmental Microbiology.* Microorganisms are the primary drivers of global biogeochemical cycles and represent the most abundant and diverse forms of life on Earth. They catalyze critical biological transformation processes such as nitrogen fixation, oceanic primary productivity, and methane cycling. Microbial ecosystem research within ESE is focused on understanding microbial processes in terrestrial, marine, and extreme ecosystems. Research areas span a range of topics and field sites, including the study of lignocellulose degradation by termite gut microbiota, anaerobic cycling of carbon, nitrogen, and sulfur in microbial mats and sediments, and methane cycling in the ocean.

Physical Facilities

ESE laboratories and facilities are housed in the Linde + Robinson Laboratory for Global Environmental Science and in other nearby buildings of Caltech's Division of Geological and Planetary Sciences. The laboratories are equipped with a wide variety of state-of-the-art instruments.

- The *Environmental Analysis Center (EAC)* houses analytical instrumentation, for research that ranges from analyzing pollutants in groundwater to dating fossils. Its equipment includes instruments for electrochemistry, plasma emission mass spectrophotometry, gas chromatography, high-performance liquid chromatography, fluorescence spectroscopy, infrared spectrometry, gas chromatography–mass spectrometry, total organic carbon analysis, and electrophoresis and electrical particle size analysis. Scientists from across the Institute use the EAC for cutting-edge analytical studies.
- The *Atmospheric Chemistry and Aerosol Laboratory* is designed for studies of the photochemical reactions of gaseous and particulate pollutants. In two reaction chambers (28 m^3 each)—the first of their kind when they were built—the chemical reactions that produce urban smog and atmospheric particles are investigated under precisely controllable conditions. They have revealed how the particles that make up smog form in the atmosphere. Research results obtained with them have been instrumental in designing effective air quality policies. They continue to be invaluable in studies of air pollution.

- The *High-Precision Spectroscopy Laboratory* is housed in a quiet room—a room with specially designed acoustic and electromagnetic insulation. Acoustic foam blocks sound waves and copper cladding around the entire room blocks electromagnetic waves. The noise-free environment allows us to achieve exquisite precision in laser measurements of radiative properties of greenhouse gases, aerosols, and atmospheric trace constituents: the properties of single molecules can be measured. The measurements are the basis for climate models and for planning satellite missions to measure the composition of the atmosphere from space.
- In the *Laboratory for Atmospheric Chemical Physics,* the interactions of light with molecules in the atmosphere are investigated to elucidate how pollution forms and to measure the atmospheric concentration of aerosols and greenhouse gases. Techniques are developed for the global monitoring of the atmosphere from mobile ground-based laboratories and from space-based instruments.
- In the *Environmental Chemistry and Technology Laboratory,* collimated sunlight from the Linde + Robinson solar telescope is focused into photolysis reactors, where artificial photosynthesis processes are developed to convert water and carbon dioxide into energetic fuels. Additionally, the chemical nature of the air-water interface is studied, and new technologies are developed for storing electric energy in novel lithium-air batteries and for treating water, for example, by photovoltaically powered electrolysis or ultrasonically induced cavitation.
- The *Geochemistry Clean Room* is designed for trace metal analysis in an entirely metal-free environment. It has air cleansed of almost all particles, to be able to measure with high precision tiny traces of metals and radioactive isotopes found in ocean water and embedded in corals and in stalagmites. These measurements reveal information about how climate has varied in Earth's past and how carbon cycles between the biosphere, the atmosphere, and the oceans. The Clean Room is supported by a plasma mass spectrometry instrument room that contains two multi-collector instruments and a quadrapole instrument. The facility also contains a wet chemistry laboratory for the processing and analysis of environmental samples.
- The *Biogeochemistry Laboratories* provide capabilities for analyzing the structure, abundance, and isotopic composition of organic materials in environmental samples, ranging from organisms to sediments to rocks. Instrumentation includes gas chromatograph–mass spectrometers, isotope-ratio mass spectrometers with capabilities for bulk and compound-specific analysis, a spectroscopic water isotope analyzer, and a combustion elemental analyzer.
- In the *Environmental Microbiology Laboratories*, the diversity and metabolic activities of microorganisms from terrestrial and marine ecosystems are characterized through cultivation,

microscopic imaging, metagenomics, and molecular and isotopic analysis. Instrumentation includes anaerobic chambers, platforms for performing microfluidics-based analyses of the nucleic acid contents of environmental single cells, capillary sequencers, quantitative PCR, epifluorescence microscopes, and CAMECA secondary ion mass spectrometers (7f Geo and nanoSIMS 50L) available through the Center for Microanalysis.

- *Fram High Performance Computing (HPC) Cluster* Fram is a (HPC) Cluster composed of 314 HP SL390 computer nodes with 12 cores available per node. The cluster is connected with a low latency, high bandwidth network called InfiniBand. In addition to the traditional computer nodes, it also has 60 GPU based nodes with a total of 180 Nvidia M2090 GPUs. This filesystem can perform at around 9.5 GB/s. Fram is the latest of many clusters used for analysis and simulation of climate dynamics.

Additionally, Caltech collaborates with the Naval Postgraduate School's Center for Interdisciplinary Remotely Piloted Aircraft Studies (Monterey, California). This center operates research aircraft for atmosphere science studies, including a Twin Otter aircraft that carries state-of-the-art instruments to measure atmospheric aerosol and cloud properties in situ. Faculty, students, and staff in the ESE program also have access to the supercomputer facility of the Division of Geological and Planetary Sciences, where they carry out simulations of dynamical processes in the atmosphere and oceans and of chemical reactions and transport processes affecting atmospheric chemistry.

GEOLOGICAL AND PLANETARY SCIENCES

Students and faculty in the Division of Geological and Planetary Sciences study Earth and the planets to understand their origin, constitution, and development, and the effect of the resulting physical and chemical environments on the history of life and on humanity. The approach to these problems relies strongly on the basic sciences. Programs of study and research are pursued in environmental science and engineering, geobiology, geochemistry, geology, geophysics, and planetary science. The curriculum is flexible so that students with degrees in biology, chemistry, engineering, or physics may carry out graduate work within the division, and interdisciplinary studies are encouraged.

Southern California provides an excellent natural laboratory for the study of geology, tectonics, and earthquakes. Current advances in understanding the dynamic motions of Earth's interior have opened new opportunities for the study of crustal motions and earthquakes. Historic records of seismic activity are put into long- term perspective by studies of surface and bedrock geology. The dynamics and geometry of crustal movements are studied on local, regional, and global scales in order to understand the evolution of continents, subduction zones, and mid-ocean ridges. The division maintains active field programs in diverse areas in North America and throughout the world.

The events that shaped Earth can be identified by studying the structure of rocks and their chemical and isotopic compositions. The absolute chronology of Earth and solar system history can be established by measurements of radioactive isotopes. These geological events have been intimately associated with the origin and evolution of life on Earth. The field of geobiology uses both geological and genetic evidence to examine the impact of life on Earth and the impact of geological conditions on biology. The field of geochemistry includes studies of radiogenic and stable isotopes, petrology, chemical oceanography, and atmospheric chemistry. These tools are applied to the origins of igneous and metamorphic rocks, evidence of past climate change, tracing anthropogenic influences on Earth, and the structure of planetary interiors. The comparative study of the other planets—their atmospheres, surfaces, and internal structures—is important in our understanding of Earth and its place in the cosmos. The early history of the solar system can be approached by studies of extraterrestrial materials, including lunar samples, interplanetary dust grains, and meteorites.

Physical Facilities

The division is housed in four adjacent buildings, which are well equipped for modern instruction and laboratory work. They contain several seminar rooms and a library as well as student and faculty offices. Numerous computers are distributed throughout the division, including a facility for geographic information systems and remote sensing. Many efforts within the division-related geodetic, geological, and seismological investigation and monitoring of plate boundary regions are coordinated through the Caltech Tectonics Observatory. The division operates a 314-node (or equivalently 3768-core) with 180 GPGPUs supercomputer used for studies in Earth and Planetary studies. Rock and mineral collections and sample preparation areas are available. There are modern laboratories equipped with a scanning electron microscope and electron microprobe; a variety of plasma-source, gas-source, thermal emission, and secondary ion mass spectrometers; optical-, infrared-, and Raman spectrometers; high-temperature furnaces and high-pressure apparatus including piston-cylinder, multi-anvil, diamond anvil, and shock-wave facilities. Cooperation with other departments on campus provides access to additional instrumentation for sample preparation and analysis.

A laboratory for molecular geobiology specializes in the culturing and the biochemical and genetic study of anaerobic bacteria. A sensitive magnetometer facility is designed for the study of both biomagnetism and paleomagnetics. The Seismological Laboratory, housed in the GPS division, operates the Southern California Seismic Network jointly with the U.S. Geological Survey. The network records and analyzes real-time earthquake data from more than 380 seismic stations located across Southern California. Data from the network are available for research via the Southern California Earthquake Data Center.

The Jet Propulsion Laboratory, NASA's lead center for planetary exploration, is located seven miles from campus and is administered by the Institute. Students and faculty participate in JPL activities through joint research, instrument development, mission operations, and data analysis. In addition, Caltech owns and operates several optical and radio observatories that are used partly for planetary research. Active programs of planetary studies are pursued at the Owens Valley Radio Observatory, Palomar Mountain, and the Keck Telescopes and, in the near future, the Thirty-Meter Telescope project.

HISTORY AND PHILOSOPHY OF SCIENCE

The program in history and philosophy of science is devoted to the study of the historical evolution and philosophical underpinnings of the physical and biological sciences. Work in history and philosophy of science may be pursued as an undergraduate option, a graduate minor, or on a course-by-course basis.

Historical research in the program includes the origins of experimental practice, the social and institutional contexts of science, the origins and applications of quantitative methods, specific developments since antiquity in physics, biology, and chemistry, as well as biographical and comparative studies. Philosophical research in the program deals with issues in causation, explanation, scientific inference, the foundations of probability and decision theory, philosophy of mind, psychology and neuroscience, and scientific fraud and misconduct.

HUMANITIES

English at Caltech spans the major periods of American and British writing. Students can pursue interests ranging from Shakespeare and a survey of drama to romantic and modern poetry; from early fiction to the postmodern novel.

History at Caltech examines the Western and non-Western past to understand the evolution of culture, science, institutions, and behavior. Courses span the medieval, Renaissance, and modern periods; the United States, Europe, and Asia; and special topics such as radicalism and demography. In certain courses, quantitative methods drawn from the social sciences are applied to historical studies.

Philosophy is concerned with the most fundamental issues involving the nature of the world and of human knowledge, values, and judgment. At Caltech, particular emphasis is placed on philosophy of the natural and social sciences, scientific inference, moral and political philosophy, and philosophy of mind, psychology, and the neurosciences. Members of the faculty have a variety of other interests, including philosophical logic, moral psychology, and the history of philosophy.

Courses in English, film history, and philosophy are given at both introductory and advanced levels.

A variety of courses in classical and modern European languages and in music and art history are available. Art history classes make use of the resources of the Huntington Library, Art Collections, and Botanical Gardens; the Los Angeles County Museum of Art; and other museums in the area.

Areas of Research

The English faculty, interested in new approaches to studying their subject, engage in research into the relationships between literature and the pictorial arts, literature and history, and the material production of literature.

Research in history covers a wide range of historical fields and methodologies. Topics include an examination of the development of racial attitudes and behavior in the 19th-century United States; the history of the physical and biological sciences and of science in relationship to society; history and film; and political and economic development in early modern Europe. A number of faculty carry out research and teaching in the interrelated subjects of science, ethics, and public policy.

Research in philosophy includes work in philosophy of science, philosophy of mind, history of philosophy, ethics, the evolution of cognition, and political philosophy.

INTERDISCIPLINARY STUDIES PROGRAM

Interdisciplinary studies offer an educational alternative for undergraduates whose goals cannot be satisfied with a normal undergraduate option. The student gathers a two-person faculty committee, representing at least two divisions of the Institute, and chooses his or her own scholastic requirements under this committee's supervision. Approval must also be obtained from the Curriculum Committee, a standing committee of the faculty. The interdisciplinary studies program has no facilities of its own. Areas of study and research may be selected from any part of the Institute. (For a complete description, see page 275.)

INFORMATION SCIENCE AND TECHNOLOGY

Information science and technology (IST) is a multidivisional research area that includes participants from the biology, chemistry and chemical engineering, engineering and applied science, humanities and social sciences, and physics, mathematics and astronomy divisions. Areas of emphasis include networking and distributed systems, neuromorphic engineering and sensory-based machines, quantum computation and communications, molecular electronics and biochemical computing, biological circuit design, information flow in economic and social systems, and mathematical foundations of information.

Physical Facilities
IST is mainly centered around the Annenberg Center for Information Science and Technology and the Moore Laboratory. Research centers associated with IST include the Lee Center for Advanced Networking, the Center for Neuromorphic Systems Engineering, the Center for Biological Circuit Design, the Center for the Mathematics of Information, the Center for the Physics of Information, and the Social and Information Science Laboratory.

MATERIALS SCIENCE

Materials scientists study relationships between the properties of materials and their internal structure, and how this structure can be controlled. The field of materials science at the California Institute of Technology emphasizes fundamental issues in metals, oxides, semiconductors, ceramics, and composites. Additional faculty in electrical engineering, applied physics, and chemistry are also concerned with semiconductors and superconductors. Work in polymers is carried out in aerospace engineering, chemistry, and chemical engineering.

Areas of Research
The current areas of research by the materials science faculty include a wide variety of nontraditional materials, many far removed from their equilibrium thermodynamic states. Examples of such materials include metallic glasses, metal-matrix composites, energy-storage materials, nanostructured materials, proton-conducting solid acids and perovskites, and materials for electronic devices. The physical characteristics of interest span a wide range of mechanical, thermodynamic, electrical, magnetic, and electrochemical properties. Materials science is a cross-disciplinary field, and graduate students in the materials science option can perform their thesis research with a supervisor or cosupervisor in a different option at Caltech.

Physical Facilities
Research by the faculty, graduate students, and a few advanced undergraduates is conducted in the W.M. Keck Laboratory, the Steele Laboratory, and frequently in the Kavli Nanoscience Institute (KNI), located in the subbasement of the Steele building. Microfabrication facilities in the KNI include standard thin-film deposition techniques, a lithography bay, and an etch bay, as well as an electron-beam and laser writers and a suite of nanocharacterization tools, such as focused ion beams (FIB), scanning electron microscopes (SEM), a nanoprobe, and a

transmission electron microscope (TEM). Material-preparation facilities include equipment for physical vapor deposition under ultra-high vacuum conditions, arc melting, induction melting, casting, rapid solidification, processing of ceramic powders, and high-energy ball milling.

Facilities for the characterization of materials include X-ray powder diffractometers with position-sensitive detectors, and a transmission electron microscopy facility has been built around an FEI Tecnai TF30 300-keV instrument with high resolution and analytical capabilities. More specialized instruments include impedance spectrometers for transport and dielectric measurements, Mössbauer spectrometers, differential scanning calorimeters and differential thermal analyzers, thermogravimetric analyzers, gas adsorption analyzers, and several test systems for the measurement of mechanical properties. In addition to the general-use equipment within materials science, a wide range of mechanical and microstructural characterization facilities are available elsewhere at Caltech including a scanning electron microscope with electron backscatter detectors, mechanical testers, nanoindenters, an in-situ mechanical deformation instrument, SEMentor, AFM, electrochemical instrumentation, and an electrical probe tester.

MATHEMATICS

Areas of Research

Students in mathematics have the opportunity to work in many fields of current research. The main active areas of research by the faculty include the following:

- *Algebra.* Finite group theory, algebraic groups, representation theory, symmetric functions, algebraic K-theory.
- *Algebraic Geometry.* Moduli spaces, birational geometry, Hodge theory, Calabi-Yau varieties, arithmetic geometry.
- *Analysis.* Classical real and complex analysis, harmonic analysis, functional analysis and operator theory, orthogonal polynomials; complex, smooth, and random dynamical and Hamiltonian systems, fractals, integrable systems, partial differential equations.
- *Combinatorics.* Combinatorial designs and matrix theory, coding theory, extremal set theory.
- *Geometry and Topology.* Low-dimensional topology, hyperbolic geometry, geometric group theory and foliations; symplectic geometry and topology, topological gauge theory, knot theory, and their interface with theoretical physics.
- *Mathematical Logic.* Set theory and its interactions with analysis, combinatorics, dynamical systems, and model theory.
- *Mathematical Physics.* Schrödinger operators, random matrices.
- *Noncommutative Geometry.*
- *Number Theory.* Algebraic number theory, automorphic forms, Shimura varieties, Galois representations, and L-functions.

Physical Facilities
The mathematics department occupies three floors of the Sloan Laboratory of Mathematics and Physics. In addition to offices for the faculty and graduate students, there are classrooms, a lecture hall, a computer lab, and a lounge for informal gatherings of the students and staff. The mathematics library is housed nearby in the Millikan Library.

MECHANICAL ENGINEERING

Mechanical engineering at Caltech explores the boundaries between traditional disciplines of science and engineering in order to develop a fundamental understanding of interdisciplinary challenges and create advanced technology to address contemporary problems. Mechanical engineering encompasses three broad areas: (1) mechanics of materials, (2) systems and control, and (3) thermal sciences and fluid dynamics.

The educational program in mechanical engineering prepares students for research and professional practice in an era of rapidly advancing technology. It combines a strong background in the basic and engineering sciences with emphasis on addressing the critical technological challenges of the day. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Areas of Research

- *Mechanics of Materials.* Studies in the field of mechanics of materials emphasize a fundamental understanding of mechanical behavior and failure of materials as well as its applications. Areas of interest include static and dynamic deformation and failure of homogeneous and heterogeneous solids, mechanical behavior of nanostructures, active materials, microstructure characterization and evolution, thin films, micro-electro-mechanical systems (MEMS), composites, fracture and frictional sliding of solids, earthquake source processes, seismo-mechanics, geomechanics, and granular media. Most problems emphasize bridging temporal and spatial scales and development of advanced analytical, computational, or experimental techniques.
- *Systems and Control.* This area combines a broad range of mechanical engineering fields, including control systems, dynamics, kinematics, and mechanical design, as well as cross-disciplinary areas such as signal processing, computer control, engineering computation, electromechanical design, micro-electro-mechanical systems (MEMS) design, and bioengineering. General areas of interest include control theory, estimation theory, decision theory, and robotics.
- *Thermal Sciences and Fluid Dynamics.* This area encompasses experimental and computational research in fluid dynamics, heat and mass transfer, thermodynamics, and combustion. Specific research areas include Stokesian dynamics, granular

materials, cavitation and multiphase flow, turbulent combustion, explosion dynamics, and flow-generated sound. Applications cover a range of scales from molecular to high Reynolds number flows, and include constitutive modeling of colloidal dispersions, micro/nanofluidic systems including Marangoni and thermo-capillary forcing in thin liquid films, formation of pollutants from combustion hydrocarbon fuels, instabilities of complex, reacting flows, and high-speed flows with shock waves. Inter-disciplinary activities in the group include research on geophysical phenomena, biomedical devices, bio-inspired propulsion, and application of control theory to fluid mechanics.

Physical Facilities
Students and faculty in mechanical engineering conduct research in laboratory facilities in a number of areas, including design and prototyping, flow visualization, heat transfer, robotics, bio/nano- mechanics, nano-mechanical testing, seismo-mechanics, biomolecular circuits, autonomous vehicles, explosion dynamics, T5 hypervelocity flow, and geomechanics. A number of High Performance Computing (HPC) clusters are available, including both CPU- and GPU-based architectures. Kavli Nanoscience Institute (KNI) is utilized for micro- and nano-fabrication, testing, and characterization.

MEDICAL ENGINEERING

Medical Engineering at Caltech focuses on the applications of micro-/nanoscale engineering sciences and technologies to the design, analysis, and implementation of diagnostic, therapeutic, and monitoring devices for translational medicine.

Areas of Research
- *Micro/Nano Medical Technologies and Devices* (Burdick, Choo, Dabiri, Emami, Faraon, Gharib, Greer, Hajimiri, Ismagilov, Scherer, Shapiro, Tai, Wang, Yang)
  Biochips, bio-MEMS/NEMS, micro-/nano-fabrication for medical applications.
- *Wireless Medical Technologies* (Emami, Hajimiri, Gharib, Scherer, Shapiro, Tai)
  Wireless communications through skins and tissues for medical electronic implants, electrograms, and biotic/abiotic interfaces.
- *Medical Nanoelectronics* (Emami, Hajimiri, Scherer)
  Integrated nanoelectronics and circuits for medical applications, extremely low power medical electronics and sensors, high ban width wireless communication devices, self-healing circuits and systems, on-chip tera-hertz sources, and systems-on-a-chip.
- *Medical Diagnostic and Monitoring On-Chip Devices* (Hajimiri, Ismagilov, Scherer, Tai, and Yang)
  Magnetic spectroscopy, bioassay, and drug-screening platforms,

micro-PCR and sequencer, and on-chip bio-sensors.

- *Medical Diagnostic, Monitoring, and Therapeutic Implants* (Choo, Emami, Scherer, and Tai)
  Microscale implants with new functionalities to interface intact tissues and/or to replace defective functions: retinal implants, spinal cord implants, ECG implants, cardiovascular implants, implantable pressure sensors, glucose sensors, drug delivery pumps, and implantable bio-analyte sensors.
- *Biomaterials* (Grubbs, Greer, Shapiro, Tai)
  Biocompatible medical materials, nanoscale-engineered smart materials, device-tissue interface, and cell-material interactions.
- *Nano & Micro Fluidics* (Dabiri, Gharib, Ismagilov, Tai, Wang)
  Micro-/nano-fluidics, drug delivery, and physiological machines.
- *Medical Imaging and Sensing* (Choo, Colonius, Emami, Faraon, Gharib, Greer, Hajimiri, Scherer, Wang, Yang)
  Medical photonics and sensors, advanced imaging technologies, micro flow-field imaging, computational image analysis, lensless microscopy-on-a-chip, diagnostic and therapeutic ultrasound and shock waves, single-molecule detection and diagnostics, magnetic spectroscopy, tera-hertz imaging, Raman spectroscpy, and non-invasive label-free biomedical imaging.
- *Biomechanics & Bio-Inspired Design* (Burdick, Choo, Colonius, Dabiri, Gharib)
  Bio-inspired self-propulsion technologies, control systems, optimization techniques, and shape morphing, cardiovascular mechanics, and muscle and membrane mechanics.
- *Prosthetics* (Burdick, Emami, Tai)
  Neural prosthetics and direct brain-machine interfaces, human prosthetics for paralysis, pure-thought-based control of external electromechanical devices, computer-decoding algorithms for direct brain interface, and robotic fingers.
- *Affordable Medical Devices and Technologies* (Gharib, Ismagilov, Pickar, Yang) Chairs for children with cerebral palsy, bed-sore mitigation, toxic material filters, saliva-based diabetes tests, and remote medical tracking systems. Devices which provide freedom from disability.

MICROBIOLOGY

Microbiology recognizes that microbial inventions have profoundly shaped every aspect of the biosphere and geosphere throughout Earth history. Many important molecular and cellular processes in eukaryotes are now known to have first arisen in bacteria and archaea, and microbial metabolic activities control numerous geochemical cycles. Microorganisms have served and will continue to serve as model systems in many areas of science, ranging from basic biology and biochemistry, to the understanding of physical principles governing biological systems, to emerging questions of robustness, stability, and design in complex networks. Interactions among microbes within communities, as well as interactions between microbial communities and their environments, are poorly understood. Yet studying these interactions is key to understanding fundamental relationships in nature, such as: 1.) the feedback loops connecting microbial activities in aquatic or terrestrial habitats with changes in composition of the atmosphere, hydrosphere and geosphere, and 2.) the symbiotic associations that sustain diverse forms of life today. For example, the interactions between a mammalian host and its microbiota are essential to the host's normal functioning and development, not merely the cause of infectious disease. Due to their metabolic versatility, microorganisms are likely to emerge as key engineering components for solving global societal problems, ranging from human health, to energy, to providing clean water to more than one billion people who currently live without it.

Caltech's version of microbiology is unique. Diverse faculty from four divisions (BBE, CCE, GPS, EAS) work together to train students in how to understand microbial systems at various spatial and temporal scales: from the molecular to the global, from the present to the past. This interdisciplinary training involves study of molecular and cellular biology, physiology, chemistry, ecology, and quantitative reasoning.

NEUROBIOLOGY

Understanding the brain remains one of the great intellectual challenges for science. To grasp the function of this marvelous organ, one needs to investigate structures, mechanisms, and dynamics that span across many spatial and temporal scales. For example, when we hear a sound, our brain is sensitive to time delays of just a few microseconds, yet the memory of that sound can last a lifetime—11 orders of magnitude longer. The span is similar in the spatial domain. The sheer number of nerve cells in the brain, approximately 10^{11}, suggests a coarse-grained treatment that glosses over the details of the individual neurons, yet a single nerve cell and even a single molecule can play a decisive role. For example, activation of a single light receptor in our eye leads to a visual percept that can ultimately direct our behavio

Neurobiology at Caltech does, indeed, span this range. Our laboratories work on the molecular structure and function of channels and receptors; the integration of such molecules into signaling organelles like the synapse; the structure and function of single neurons; the integration of neurons of diverse types into circuits; and the collective function of these circuits in controlling behavior, perception, memory, action, cognition, and emotion. Another area of emphasis concerns the developmental mechanisms by which these structures form: the differentiation of neurons in early life, the genetic mechanisms that guide their synaptic wiring plan, and how subsequent experience modifies these connections. There is also increasing interest in leveraging the basic neurobiological insights to an understanding of brain disorders.

Finally, Caltech's traditional strength in engineering stimulates the development of new methods for brain science: from optical techniques to new twists of genetic engineering, to novel multi-electrode devices, to computational models and theories.

To further explore the range of brain research at Caltech—and enjoy some colorful pictures—please visit the Neurobiology option website.

PHYSICS

Areas of Research

Students in physics will find opportunities for research in a number of areas where members of the faculty are currently active, including those listed below. Physics research at Caltech is often done in collaboration with scientists in the departments of applied physics, astrophysics, planetary science, engineering, chemistry, biology, and other departments, as well as with collaborators at other universities and laboratories. Additional research programs and more detailed information can be found on the Caltech physics department website.

- *Experimental Elementary Particle Physics.* Activities in elementary particle physics are aimed primarily at finding physics beyond the Standard Model. Experimental efforts employ hadronic colliders, e+e- colliders, and neutrino beams at several international facilities. Current experiments include the Large Hadron Collider at CERN, which is searching for the Higgs boson and physics beyond the Standard Model; the MINOS and Nona experiments at Fermilab, studying long baseline neutrino interactions; the BABAR and follow-up experiments, searching for new physics in CP-violating and other rare processes in B meson and t lepton decays.
- *Theoretical Elementary Particle Physics.* The particle theory group studies the unification of interactions based on string theory, the detailed properties of hadrons described by QCD, the quantum properties of black holes, the foundations of cosmology, including dark matter and dark energy, and other aspects of mathematical physics.
- *Nuclear Physics.* The interests of the nuclear group include understanding the detailed properties of neutrinos and performing precision nuclear measurements to search for physics beyond the Standard Model. Neutrino oscillations are investigated at off-campus facilities using accelerators and antineutrinos produced in reactors to provide detailed information on the relative neutrino masses and mixing properties. Precision measurements of neutron decay allow sensitive searches for new physics, while measurements of the neutron electric dipole moment may help explain the dominance of matter over antimatter in the universe.

- *Observational Astrophysics.* Research in this area covers a broad range of topics using observational tools covering the entire electromagnetic spectrum. The high-energy astrophysics group at the Space Radiation Laboratory (SRL) uses X-ray and gamma-ray detectors aboard spacecraft and balloons to investigate energetic processes from compact astrophysical objects, including gamma-ray bursts from neutron-star and black-hole systems, supernova and hypernova dynamics, and the development of stars and galaxies in the early universe.

  The cosmic ray group at SRL uses data from a variety of spacecraft to study the composition of energetic particles arriving from the sun, the local interstellar medium, and beyond, in order to understand the origin and acceleration of energetic particles in space.

  The ultraviolet astronomy group uses satellite observations, such as from the GALEX spacecraft, to explore the ultraviolet sky. Studies include the birth and death of stars, galaxy dynamics and evolution, and other areas.

  The submillimeter astronomy group studies star formation, interstellar gas, galaxies, and quasars using the Caltech Submillimeter Observatory and other facilities. An active program is also under way to develop new superconducting detector technologies for use at these wavelengths, in collaboration with scientists at the Jet Propulsion Laboratory.

  The infrared astronomy group studies a host of astrophysical phenomena using Caltech's Palomar Observatory, the twin 10-meter optical telescopes at the Keck Observatory, and observations from the Spitzer Space Telescope. Caltech also manages the Spitzer Science Center on campus.
- *Theoretical Astrophysics.* The TAPIR (Theoretical Astrophysics Including Relativity) group carries out research on an ever-changing list of topics, including high-energy astrophysics and the physics of black holes and neutron stars, gravitational-wave astrophysics, cosmology, the formation of stars and galaxies in the early universe, and general relativity.
- *Cosmology*. The observational cosmology group explores the structure and dynamics of the early universe using precise measurements of the cosmological microwave background radiation from detectors on the ground, on balloons, and on spacecraft. Efforts to directly detect dark matter are also under way. These experiments include an active program of detector development in collaboration with scientists at the Jet Propulsion Laboratory. Theoretical studies seek to understand the large-scale structure of the universe, including the physical nature of dark matter and dark energy.
- *Gravitational-wave Astronomy.* Observations from the LIGO and LISA projects seek to use gravitational radiation to study a variety of astrophysical sources. Theoretical studies are aimed at developing sensitive data analysis techniques and calculating

G-wave signals from sources such as coalescing black holes and neutron stars.

- *Condensed-Matter Physics.* Areas of interest include correlated electron systems, 2-D matter, phase transitions, atomic and excitonic Bose condensation, nanomechanical and nanoelectronic systems, biosensors, quantum electromechanics, phonon physics, high-temperature superconductivity, graphene and carbon nanotube systems, quantum entanglement, dynamics of disordered systems, chaos, pattern formation, and systems far from equilibrium. Resources include numerous labs in the Caltech physics department, at the Kavli Nanoscience Institute at Caltech, and at the Jet Propulsion Laboratory.
- *Quantum Optics and Information.* Research on campus and at the Institute for Quantum Information at Caltech includes studies of the nature of quantum computation and quantum information, cavity quantum electrodynamics, algorithms and error correction techniques in quantum computation, and generally how quantum physics can be harnessed to improve the acquisition, transmission, and processing of information.

Physical Facilities
The physics and astrophysics departments and laboratories are mainly housed in six buildings on campus: the Norman Bridge Laboratory, the Alfred P. Sloan Laboratory of Mathematics and Physics, the W. K. Kellogg Radiation Laboratory, the George W. Downs Laboratory of Physics, the C. C. Lauritsen Laboratory of High Energy Physics, and the Cahill Center for Astronomy and Astrophysics. Off-campus astronomical facilities include Palomar Observatory, the Keck Observatories, Owens Valley Radio Observatory, the Caltech Submillimeter Observatory, the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and the Laser Interferometer Gravitational-Wave Observatory (LIGO).

SOCIAL SCIENCE

The social science program at Caltech is highly interdisciplinary, integrating economics, political science, quantitative history, law, anthropology, and psychology. It makes extensive use of mathematical modeling, laboratory experiments, and econometric techniques. Social science at Caltech strongly emphasizes the understanding and analysis of the relationships between individual incentives, political and economic institutions, and public policy.

Areas of Research
Caltech social scientists are leaders in the field of laboratory experimentation. They have focused upon the behavior and design of auctions and auction-like mechanisms, public goods provision, interpersonal bargaining, and committee decision making. Considerable

laboratory experimentation also focuses upon the workings of financial markets, and seeks to elucidate basic principles that underlie the pricing of assets, trading, and information aggregation in these markets. Many of these experiments are conducted through the use of networked computers in the William D. Hacker Social Science Experimental Laboratory.

In recent years, new avenues of experimentation in social science have emerged with advances in neuroscience. Utilizing fMRI brain-imaging, eye-tracking, and other measurement technologies, research at Caltech has begun to explore the neural foundations of decision making in game theoretic and market settings. The real world provides another setting for experimental research, and Caltech social scientists have conducted game theoretic-based experiments involving a wide variety of subjects, ranging from urban Americans to African villagers.

In the area of economic theory, research at Caltech has played a major role in the design of new institutions that more efficiently allocate resources and provide public goods. There has also been considerable research at Caltech on developing better theoretical and statistical models of individual choice behavior.

Political scientists at Caltech focus primarily upon quantitative analyses of voting, legislative behavior, and public policy. They draw heavily upon techniques and approaches used in a variety of other disciplines, such as economics, statistics, and legal studies. During the past decade Caltech faculty members have been active contributors to the Voting Technology Project, a joint Caltech-MIT research effort that evaluates the performance and reliability of U.S. balloting technology, registration systems, and election administration. Caltech political scientists have also pioneered techniques for the detection of vote fraud and other election anomalies.

As in the case of economics and political science, historical research conducted at Caltech employs mathematical modeling and sophisticated statistical techniques to attack a wide range of historical questions. These include the development of capital markets in Europe, the impact of racial discrimination in the United States, the causes of recurrent financial crises in capitalist economies, and the determinants of economic growth.

SYSTEMS BIOLOGY

Systems Biology seeks to understand how the parts of biological systems are integrated to produce the amazing machines, cells, organisms and ecosystems that exist in our world. We seek to define general principles of biological systems. Part of the effort involves defining the relevant parts and measuring how they change in a quantitative and comprehensive fashion as they carry out their functions. This task is the domain of genomics, proteomics, metabolomics, functional genomics, bioinformatics and other aspects of Network Biology and Bioinformatics. Another related task is to understand the "mechanisms," the precise structures and interactions of those parts that ultimately produce biological function. This task requires Computational Modeling of potential mechanisms, coupled with Quantitative tests of the predictions of models by cell biological, molecular biological, and biophysical techniques. One particularly stunning feature of organisms is their ability to develop from a single fertilized egg; thus, Systems Developmental Biology is an important third theme of our program. This theme involves the study of how organisms generate complexity of cell types in a defined spatial organization by a sequential, contingent, irreversible cascade of molecular, cellular, and genomic processes.

Our goal is to train students who can seamlessly integrate diverse quantitative and experimental methodology and can balance the tension between global understanding and mechanistic insight. This training involves study of biology, mathematics, quantitative reasoning, computational and data analysis tools, and the rich experimental methods of the biological sciences.

Information for Undergraduate Students

The undergraduate program leads to a four-year Bachelor of Science degree. Admitted students matriculate in the fall term only. Caltech does not have a summer session or part-time program and cannot consider you if you already have a bachelor's degree from another college, university, or the equivalent. If you have matriculated at any college, university, or the equivalent in a program leading to any degree, you will be required to apply as a transfer student and should read the requirements in the section titled "Transfer Admissions."

ADMISSION TO THE FRESHMAN CLASS

Students are admitted to the freshman class on the basis of strong academic performance in a rigorous course of college preparatory study, especially in the areas of math and science; results of the SAT or ACT, and one SAT science subject test and the SAT mathematics level 2 test; teacher and counselor evaluations; personal characteristics; a demonstrated interest in math, science, or engineering; and information provided on the application.

Applying
Information on the application process can be found on the admissions office website at http://www.admissions.caltech.edu. Students are encouraged to apply online through the Common Application. For further information on admission, please call (626) 395-6341 or e-mail ugadmissions@caltech.edu. To be considered for admission, applications to the freshman class must be submitted online by November 1 for Early Action or January 3 for Regular Decision.

Early Action
The Early Action application process requires that the completed application be submitted online by November 1. Under this application plan, students will be notified in mid-December of the admission decision. Students admitted under Early Action have until May 1 to make their commitment to attend.

High School Requirements
Students are expected to prepare for Caltech by successfully completing the following curriculum:

Four years of mathematics (including calculus)
One year of physics
One year of chemistry
Three years of English (four years recommended)
One year of U.S. history/government (waived for international students)

Standardized Exams
Applicants are required to take the following standardized tests by the October test series for Early Action consideration, and by the December test series for Regular Decision consideration:

SAT w/writing or ACT w/writing
SAT mathematics level 2
One of the following SAT subject tests: Biology (molecular or eco logical), Chemistry, or Physics
TOEFL (for international applicants)

Information regarding the College Board examinations can be found online at https://www.collegeboard.org, or by contacting the College Board, 45 Columbus Avenue, New York, NY 10023-6992;
(212) 713-8000. For ACT, 500 ACT Drive, P.O. Box 168, Iowa City, IA 52243-0168; (319) 337-1270; http://www.act.org.

Essays
The essays, which are required as a part of the application, are intended to provide students the opportunity to communicate their interests, experiences, and background. Since Caltech is interested in learning about each applicant, the essays are viewed as an important part of the admission decision process.

Evaluations
Two evaluations and a Secondary School Report are required. One must be from a math or science teacher, and one from a humanities or social science teacher (see the instructions in the application).
A Secondary School Report must be filled out by the applicant's high-school counselor or other school official.

Additional Material
Descriptions of research projects and hands-on science and engineering experience are helpful, as is material that demonstrates experiences outside math and science. Additional material should be identified with name and date of birth.

Acceptance
Caltech is a National Association for College Admissions Counseling member and therefore agrees to comply with the candidate's reply date of May 1. Places in the entering class will not be held after May 1. Early Action applicants will be informed of their status in mid-December, and Regular Decision applicants will be informed by April 1.

Deferral of Entrance
For reasons of travel or work, Caltech will consider requests from admitted students for a one-year deferral of entrance. Students who request a deferment must submit a written request stating the purpose of postponement.

Advanced Placement, International Baccalaureate, and College Credit
Caltech encourages all prospective undergraduate applicants to prepare by challenging themselves with the most rigorous course of study available, including the Advanced Placement (AP) and International Baccalaureate (IB) programs. However, college credit for AP or IB classes is not automatic. Course credit and/or placement in an accelerated program is *sometimes* granted as deemed appropriate by the department faculty. The awarding of Caltech course credit takes place at the time of registration each fall.

Biology
Biology majors who have passed Bi 8 and Bi 9 are considered to have met the core requirement of Bi 1.

Chemistry
The student's qualifications for placing out of Ch 1 ab will only be determined by the performance on a placement examination to be administered in the summer prior to registration. Qualified students, with the instructor's consent, are allowed to substitute either Ch 8 or Ch/ChE 9 for the "core" chemistry laboratory requirement (Ch 3 a or Ch 3 x).

English/Writing
All incoming students (freshmen and transfers) will take a placement assessment to determine whether they are adequately prepared for the substantial writing component that is part of all freshman humanities courses. Most new students participate in a web-based version of this assessment, which is usually conducted in early June. A makeup assessment is held just before fall classes begin. Based on results of this writing assessment, students may be required to take Wr 1 or Wr 2 in the Fall quarter. (Wr 1 and Wr 2 count for general Institute credit only.) After completing these courses, students may, at the discretion of humanities faculty, be required to go on to subsequent coursework in academic writing, such as Wr 3, Wr 4, or Wr 50, before or concurrently with freshman humanities coursework. During the first week of classes, students will be required to produce an in-class writing sample to confirm the initial placement.

Mathematics
During the summer before the freshman year, entering freshmen are asked to take a diagnostic exam in basic calculus that will determine which students will be placed in a special section of Ma 1 a for those with less complete preparation, and later take Ma 1 d; and if they are interested in advanced placement, they may also take an examination to determine whether they will begin the mathematics core sequence at an advanced level.

Normally, an entering freshman takes Ma 1 abc, Calculus of One and Several Variables and Linear Algebra. This course covers the calculus of functions of one and several variables; infinite series; vector algebra; basic and advanced linear algebra; derivatives of vector functions, multiple integrals, line and path integrals; and theorems of Green and Stokes. The course is divided into a lecture part and a recitation part that focuses mainly on problem-solving.

Students in need of additional problem-solving practice may be advised to take Ma 8 (in addition to Ma 1 a) in the first quarter.

Physics

The required freshman physics course, Ph 1 abc, is considerably more rigorous than most advanced placement work, and entering freshmen are encouraged to take Ph 1. A test is administered during the summer to aid in the organization of Ph 1; students who have performed particularly well can discuss the possibilities for advanced placement with the physics representative during orientation.
A second test may then be required.

New Student Orientation

All freshmen and transfer students are expected to attend the New Student Orientation as a part of the regular registration procedure. Orientation takes place the week prior to the beginning of classes. A large number of faculty members and upperclass student leaders participate, helping to introduce the new student to the Caltech community. The orientation period provides an opportunity for new students to become acquainted with the campus, the Honor System governing personal conduct, and other aspects of life at Caltech. In addition, he or she will meet classmates, upperclass students, and faculty during this time.

ADMISSION TO UPPER CLASSES BY TRANSFER

Transfer Admissions

Caltech admits transfer students for the fall term only. We require a completed application, letters of recommendation, an official transcript from the last secondary school attended and all colleges or universities attended, descriptions of all college-level math and science courses, and completion of the Caltech Transfer Entrance Examinations. Please review the section titled "Eligibility Criteria for Admission" to determine whether you meet the eligibility requirements for transfer admissions consideration.

Academic Preparation

The following is a list of the Caltech core curriculum, taken by all Caltech students during their first two years. It is expected that transfer students will have had exposure to mathematics and science courses on a comparable level prior to entry to Caltech. Any of the following core courses that have not been covered by incoming transfer students must be taken upon matriculation to Caltech. There are no specific topics expected to have been covered in humanities and social science classes.

An evaluation of each transfer student's written English is required prior to registration and may result in an additional course requirement.

Freshman courses:

Mathematics 1 abc
Physics 1 abc
Chemistry 1 ab
Chemistry 3 a or 3 x
Biology 1, 1 x, 8, or 9
Humanities and Social Science electives
Menu science class (see page 222; can be taken freshman or sophomore year)

Sophomore courses:

Mathematics 2 and 3
Physics 2 abc or Physics 12 abc
Additional laboratory science
Humanities and Social Science electives

Eligibility Criteria for Admission

The Institute admits to its sophomore and junior classes a small number of students who have excellent records at other institutions of collegiate rank and who perform satisfactorily on the Caltech Transfer Admissions Entrance Examinations.

- Students must have completed their secondary school education, and have subsequently enrolled at a college or university and earned credit, in order to be considered for transfer admission.
- Transfer students are not admitted to the senior year at Caltech.
- Students who have already completed a bachelor's degree in any subject are not eligible for transfer.

Standardized Test Requirements

Transfer applicants are not required to submit SAT scores. The Test of English as a Foreign Language (TOEFL) is required of transfer applicants whose native language is not English and who have not been studying in an English-speaking country for two years or more. The TOEFL should be taken no later than the February test date.

Evaluation of Written English

All entering transfer students will be required to undergo an evaluation of their written English prior to enrolling.

Transfer Admissions Entrance Examinations

All applicants are required to take Caltech Transfer Admissions Entrance Examinations in mathematics and physics. Further instructions are included with the Caltech Transfer Application.

Transfer of Credit
The courses for which transfer applicants will receive credit, and the corresponding class standing, will be determined at the time of enrollment. Faculty members review each course submitted for credit on an individual basis. It is not possible, therefore, to answer questions regarding the acceptability of course work taken elsewhere. If the standard of work taken elsewhere is uncertain, additional examinations may be required before the question of credit is finally determined.

Graduation Requirements
Admitted transfer students must meet the following requirements in order to receive a Caltech Bachelor of Science degree.

- Tuition for the baccalaureate degree is based on 12 terms of residence regardless of unit load each term or if a student completes graduation requirements a term(s) early. The 12-term tuition requirement is separate from and in addition to any other degree requirements. Students who are admitted as transfer students or 3/2 students may be granted advanced standing and tuition credit for academic work accepted in transfer to Caltech. However, transfer and 3/2 students must enroll for a minimum of six terms at Caltech. Any exceptions must be approved by the undergraduate dean and the provost.
- Regardless of the amount of credit awarded upon matriculation, transfer students must spend at least two years (six terms) in residence at Caltech. Students must also earn at least 216 units at Caltech, not including courses taken to satisfy math and science core curriculum requirements.
- Students must take, or have taken the equivalent of, all core curriculum courses.
- Students must satisfy all of their chosen option's degree requirements. Transfer students may choose from among all Caltech undergraduate options.

Admissions Application
Applications are available by September 1. Completed applications should be received by the Office of Undergraduate Admissions by February 15. Applicants will be notified of the decisions of the Admissions Committee in early May. Information on the application process can be found on the admissions office website at http://www.admissions.caltech.edu. Students should apply online through the Common Application (commonapp.org). For further information on admission, please call (626) 395-6341 or e-mail ugadmissions@caltech.edu.

Nondiscrimination and Equal Opportunity
Caltech is committed to equal opportunity for all persons without regard to sex, race, creed, color, religion, national origin, ancestry, age, marital status, pregnancy, gender, gender expression, gender identity, sexual orientation, genetic information, status as disabled veteran, or

other eligible veteran, for otherwise qualified individuals with a disability, or any other condition protected by the state and federal law. It is the policy of Caltech to provide a work and academic environment free of discrimination as required by federal and state law, including Title IX which prohibits discrimination based on sex in Caltech's educational programs and activities. Caltech will take all reasonable steps to eliminate discrimination, harassment, and sexual violence in its work and academic environment. Inquiries concerning the application of Title IX may be referred to Caltech's Title IX Coordinator, Felicia Hunt, who can be reached at TitleIXCoordinator@caltech.edu or at 626-395-3132.

The 3/2 Dual Degree Plan

Caltech invites students from a select group of liberal arts colleges to transfer to Caltech upon completion of their junior year. After two years in residence at Caltech, and the successful completion of our requirements, 3/2 students will be granted a Bachelor of Science degree from Caltech and a second bachelor's degree from their liberal arts college. Students may transfer into any of the Caltech options.

Students from the following institutions are eligible to apply to the 3/2 program:

- Bowdoin College (ME)
- Bryn Mawr (PA)
- Grinnell College (IA)
- Haverford College (PA)
- Mt. Holyoke College (MA)
- Oberlin College (OH)
- Occidental College (CA)
- Ohio Wesleyan University (OH)
- Pomona College (CA)
- Reed College (OR)
- Spelman College (GA)
- Wesleyan University (CT)
- Whitman College (WA)

Applications and a program description are available from the 3/2 liaison at each of the liberal arts college partners and from the Caltech Office of Undergraduate Admissions. Instructions on how to create and complete Caltech's online 3/2 application can be found at http://www.admissions.caltech.edu. All 3/2 applications and support materials must be submitted by April 1.

Admission to the 3/2 program is not guaranteed and will be determined by the Caltech Faculty Upperclass Admissions Committee. Students applying should have a record of superior academic achievement at their home institutions, and strong letters of recommendation from their 3/2 liaison and an additional faculty member. They must have completed a minimum of one year of calculus-based physics and mathematics (two years are recommended), including multivariable calculus and differential equations, and one year of chemistry.

Exchange Programs

Exchange programs exist with Occidental College and Art Center College of Design, permitting Caltech students to receive credit for courses taken at these colleges. Students from these colleges also may receive credit for courses taken at the Institute. Tuition payments are not required, but the student may have to pay any special fees. The student must obtain approval from the instructor of the exchange course. Exchange courses taken by Caltech students must have prior approval by the student's option, by the division providing courses most similar to the proposed course, and by the registrar. Students wishing to take such courses should obtain the appropriate form at the Registrar's Office, get the required signatures as above, and return it to the registrar. Freshmen at Caltech ordinarily cannot participate in this exchange.

STUDY ABROAD

Study abroad allows students to experience life in other countries and to gain a broader exposure to the sciences, engineering, economics/management, the social sciences, and humanities.

Please see the Financial Aid section of this catalog for details on applying for and eligibility for financial aid related to study abroad. Note that supplemental charges and travel should be listed by the student in his or her financial aid budget so that these amounts can be considered when funding is calculated.

Additional information, including application procedures and exact deadline dates, is available from the Fellowships Advising and Study Abroad Office at http://www.fasa.caltech.edu.

Cambridge Scholars Program

The Caltech Cambridge Scholars Program offers qualified juniors and seniors the opportunity to spend a fall or winter term at the University of Cambridge in England. Students are hosted by and live in one of the Cambridge Colleges participating in the program. The participating colleges are Corpus Christi, Pembroke,

St. Catharine's, and St. John's. Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There may be a small supplemental charge for room and tuition. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one Cambridge department in the biological sciences, physical sciences, computer sciences, mathematics, engineering, or economics to take classes within the tripos, i.e., subject, offered by that department. Students may only take courses in one tripos unless special permission is granted, and this is usually granted by Cambridge if a student needs a course to fulfill a Caltech option requirement. Students will find more information on the tripos structure and Cambridge University in the Fellowships Advising and Study Abroad Office or at http://www.cam.ac.uk.

During the term at Cambridge, students take the equivalent of at least 36 Caltech units, usually four Cambridge courses, but may take five in most cases. The exact number of courses depends on Cambridge departmental requirements. For their classes, students receive a minimum of 36 Caltech units that can be used for general or option credit or to fulfill other Institute course requirements. Note that the final number of units and whether the units can be used to fulfill departmental requirements will be determined after faculty review upon a student's return to Caltech.

Caltech students have the use of all Cambridge facilities and are matriculated into the university for the term. A minimum 3.4 GPA is required to apply. Eligible sophomores and juniors interested in either the fall or winter term should apply by the January deadline for the next academic year. Further information, including application procedures, more about Cambridge University, and exact deadline date, is available from the Fellowships Advising and Study Abroad Office at http://www.fasa.caltech.edu.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

Copenhagen Scholars Program

The Caltech Copenhagen Scholars Program offers qualified juniors and seniors the opportunity to spend the fall at the University of Copenhagen (KU) or the Danish Technical University (DTU), both universities in the Copenhagen metropolitan area. At KU students will find courses offered in the physical or life sciences and computer science. At DTU students can take courses in engineering, computer science, nanotechnology, applied physics, space sciences, and in a broad range of science subjects, e.g., chemistry, physics, and mathematics. Students must select KU or DTU as theire admitting university and will take all courses in the sciences/applied sciences at that university. All students are required to take a Danish language class during the semester.

Students live in a modern kollegiet (dormitory) with Danish students. There is a supplemental charge for the room due to the ~15 weeks long semester. The supplement varies yearly depending on prices and the exchange rate. Students admitted to KU live in a KU kollegiet and students admitted to DTU live in a DTU kollegiet.

There is no board plan, but each kollegiet has a well-equipped kitchen, and students may cook for themselves or with the other students on the hall. In addition to the supplemental room charge, all students pay standard board and tuition, but should budget additional funds for food due to the length of the semester. Note that while students pay Caltech board fees, the board fee is used to spend on food while in Copenhagen. Students can cook in their kollegiet or eat out. Caltech fees are due by the normal fall due date.

Both KU and DTU are on a semester system, and Caltech students attend from the last week of August to mid-December and are required to participate in the one-week orientation or advising period the last week of August. Students have a one-week vacation in mid-October, and many use this vacation week to travel in Denmark or Europe.

Students take a maximum of 30 ECTS in their Caltech option or a closely related subject. At least two classes must get option credit for. All students take a class in the Danish language offered at KU. Students attending Copenhagen University are required to take a course in Danish culture and two Block 1 and one Block 2 class.

KU admitted students may take one class taught in English on subjects such as Danish Culture, the Danish monarchy, Danish architecture, Danish film, or the Vikings, depending on what is offered that fall. In addition to lectures, many of these classes have field trips to cultural and historical sites in the city and

surrounding area. All upper-level undergraduate or beginning graduate-level courses at KU and DTU can be taught in English.

Students admitted to DTU may take a class on the history of technology, which may qualify for Humanities credit. DTU has a very intriguing group of classes in management and in technology management. These can be taken for social science or option credit with the permission of the option representative.

Students receive a minimum of 36 Caltech units (many receive more units) that can be used for general or option credit or to fulfill other Institute course requirements. Note that the final number of units and whether the units can be used to fulfill departmental requirements will be determined after faculty review upon a student's return to Caltech.

Students can enroll in an optional three-week-long Danish-language course in August at either KU or DTU depending on their admitting university. This course is not required, but all students are required to take Danish language during the fall semester for credit.

Further information about the Copenhagen Scholars Program is available in the Fellowships Advising and Study Abroad Office and online at: http://www.fasa.caltech.edu. Go to http://www.dtu.dk or http://www.ku.dk for further information on DTU or KU.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

École Polytechnique Scholars Program

The École Polytechnique Scholars Program offers qualified juniors and seniors the opportunity to spend the fall, winter, or spring term at the École Polytechnique, which is located outside of Paris in the town of Palaiseau, about 40 minutes by train from Paris. Note that the winter and spring terms can only be attended in years that do not overlap with Caltech term dates and only with the permission of École Polytechnique and Caltech. In addition, seniors may not attend the spring term if they plan to graduate in June.

The École Polytechnique (the "Polytechnic School"), often referred to by the nickname "X," is the foremost French *grande école* of engineering (according to French and international rankings). Founded in 1794 and initially located in the Latin Quarter in central Paris, it was moved to Palaiseau in 1976. It is one of the oldest and most prestigious engineering schools in the world, with a very selective entrance exam. As one of the world's foremost establishments in science education, the École Polytechnique trains graduates who become outstanding scientists, engineers, researchers, managers, and politicians.

At École Polytechnique, students can take courses in engineering or the applied sciences as well as the sciences, e.g., chemistry, physics, and math, as these are also taught. Students can also take classes in the social sciences and humanities. Two classes must be in the student's Caltech option in science, engineering, or economics and two classes can be taken in other subjects or in the student's option.

All classes are taught in French, and all discussions, assignments, and exams are in French. *Students must have very good ability in speaking, reading, and writing French **before** applying for this program.* Students will continue to take French at their level while at École Polytechnique.

École Polytechnique has different academic schedules depending on the year of study. Caltech students who study at École Polytechnique for a term (usually the fall) during their junior or senior year can only select classes from the third year of the École Polytechnique curriculum, and all classes must be selected from this year's curriculum. Note that the second-year classes are not allowed, as this year goes from the fall through January and then has a second semester versus two terms. The third-year specialized curriculum has a schedule that corresponds closely to Caltech's three-term system, and students must take all classes from the third-year curriculum. These classes are equivalent to 100-level classes at Caltech. For further information, go to this URL and scroll down to the third-year specialized education section: http://www.polytechnique.edu/page.php?MID=216.

A minimum 3.3 GPA is required to apply. Eligible sophomores and juniors apply to study during their junior or senior year by the Caltech internal deadline, which is usually in January.

Note that students must be nominated by Caltech in order to apply and cannot apply without going through the internal Caltech nomination process, which is run by the Fellowships Advising and Study Abroad Office. Only this office can provide the required nomination. Each year application specifics will be provided to sophomores and juniors in the fall. Students will be required to complete both Caltech Study Abroad Proposal and Forms and complete the École Polytechnique application forms as well as undergoing a formal assessment of French skills by Caltech's French instructor.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

Edinburgh Scholars Program

The Caltech Edinburgh Scholars Program offers qualified juniors and seniors the opportunity to spend the fall at the University of Edinburgh. The University of Edinburgh is on a semester system, and Caltech students attend from mid-September to mid-December. All students are required to attend a weeklong orientation held the week before classes start. All students live in university dormitories or flats, which are within walking distance from the George Square (humanities and social sciences) and the King's Buildings (the science and engineering campus). The university operates a free shuttle bus from the George Square campus to the King's Buildings campus.

Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for housing due to the longer length of the term. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one of Edinburgh's academic departments in the College of Science and Engineering. Note that students cannot be admitted into the economics department because that is in the College of Humanities and Social Sciences, but they can take 20 credits in that department. Students whose option is BEM or economics may be allowed in an urgent situation to take 40 credits in economics in order to fulfill BEM or economics option requirements.

Students take a minimum of 60 Edinburgh credits per semester and a maximum of 80 credits, but no more than five courses. Students will take a minimum of 40 credits in their option or another science or engineering subject and can take 20 credits (one course) in the College of Humanities and Social Sciences. Note that 60 credits is the standard courseload, but most Caltech students take 70 to 80 credits. Note that at least 36 Caltech units must be taken.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors should apply by the January deadline for the fall semester at Edinburgh. Further information, including application procedures and exact deadline dates, is available from the Fellowships Advising and Study Abroad Office: http://www.fasa.caltech.edu.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

London Scholars Program

The Caltech London Scholars Programs offers qualified juniors and seniors the opportunity to spend the fall at University College London, which is located in the lovely Bloomsbury area of London. University College London (UCL) is on a semester system, and Caltech students attend UCL's autumn semester from about the third week of September to mid-December. All students are required to attend an orientation (Wednesday evening through Friday/Saturday) the week before the semester begins. All students live in a UCL dormitory, which is located a short walk or short bus ride from the academic buildings of the UCL campus. Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for housing/board due to the longer length of the term. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one of UCL's academic departments in the physical, life, or engineering sciences and must take two UCL/30 ECTS (European Credit Transfer System) credits. Students are required by UCL to take at least 50 percent of their classes in their Admitting Department. Usually the Admitting Department is in a subject area that most closely corresponds to the student's Caltech option, but there is some leeway in this provided the student has the background to be admitted to the department in question. Note that students can be admitted to two departments in the life, physical, and engineering courses and take at least 25 percent of their classes in each. However, dual admission is only available if there is a compelling reason, e.g., double- option students who need to fulfill a course requirement.

The remaining 50 percent of classes can either be taken in the Admitting Department, another department in the sciences or engineering, or the humanities and social sciences with the exception of the English literature department, which does not admit visiting students, even those with majors in English literature. Note that there are ample opportunities to take literature courses from a number of departments that offer literature classes, e.g., Slavonic and East European studies, Classics, Scandinavian studies, European cultural studies, Hebrew and Jewish studies, French, etc. Note that these departments offer classes taught in translation and in the foreign language.

A typical UCL semester class is 7.5 ECTS or 5 ECTS credits in the sciences or life sciences. In engineering subjects, a one-semester class is typically 2.5 UCL/3.75 ECTS credits. Caltech students must take 30 ECTS credits/2 UCL units during their semester at UCL. This would be equivalent to 36 to 45 Caltech units. UCL classes can be used for general or option credit or for humanities or social science credit. Note that the final number of units and whether the units can be used to fulfill departmental requirements will be determined after faculty review upon a student's return to Caltech.

Note that students can be admitted into the economics department as a secondary department. Such students must take at least 50 percent of their classes in their primary department in the physical, life, or engineering sciences and at least 25 percent of classes in economics. Only students with a secondary admission to economics may take upper-level economics classes. Note that students can take up to two first- or second-year courses in the economics department without a formal dual admission.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors apply by the January deadline for the fall semester at UCL. Further information, including application procedures and exact deadline dates, is available from the Fellowships Advising and Study Abroad Office.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

Melbourne Scholars Program

The Caltech Melbourne Scholars Programs offers qualified juniors and seniors the opportunity to spend the summer/fall at the University of Melbourne, which is located in the exciting city of Melbourne, Australia. Melbourne is on a semester system, and Caltech students attend Melbourne's second semester from the second week of July to the end of November. Since Melbourne is in the Southern Hemisphere, the university's first semester starts in July and crosses over both the Caltech winter and spring terms. Therefore, students attend Melbourne's second semester, which corresponds better to Caltech's fall semester. All students are required to attend an orientation that takes place at the University of Melbourne the week before the semester begins.

Students live in a residence hall, which is located a short walk from the academic buildings of the campus. The hall of residence, RMIT Village, has a suite setup and offers amenities such as a 15-meter outdoor swimming pool and lounge area, barbecue area, workout gym (with plasma TV, cross trainers, free weights, treadmills, exercise bikes, etc.), café, lounge, and laundry. There is also a new e-library that offers computers and printers as well as group and individual study rooms.

Students share a suite with another student (bedroom, bathroom/shower, kitchenette, living room). Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for housing/board due to the longer length of the Melbourne semester. In some years there could be a supplemental tuition charge. The supplement varies yearly depending on prices and the exchange rate.

Students take four classes at Melbourne. Each class is worth 12.5 Melbourne credit points. Of the four classes, students must take two classes related to their option at Caltech and may take up to two outside of their subject, including the humanities and social sciences. Students are eligible to take one class as a research class in an area related to their option.

The Melbourne credit load would be equivalent to 36 to 45 Caltech units. Melbourne classes can be used for general or option credit or for humanities or social science credit. Note that the final number of units and whether the units can be used to fulfill departmental requirements will be determined after faculty review upon a student's return to Caltech.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors apply by the fall deadline for the second semester starting in July. Further information, including application procedures and exact deadline dates, is available from the Fellowships Advising and Study Abroad Office.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study abroad. Students who receive financial aid should list supplemental charges and travel in their aid application.

ROTC

Air Force Reserve Officer Training Corps (AFROTC) offers three- and four-year programs leading to a commission as a second lieutenant in the United States Air Force. The AFROTC program is open to almost all students pursuing baccalaureate degrees. Classes consist of one hour of academics and two hours of leadership laboratory per week for freshmen and sophomores, and three hours of academics and two hours of leadership laboratory per week for juniors and seniors. AFROTC offers a variety of scholarships valued at up to 100 percent of annual tuition, along with a nontaxable monthly stipend. By agreement through the Air Force, Caltech students enroll in Air Force ROTC classes at the University of Southern California, California State University San Bernardino, Loyola Marymount University, or the University of California, Los Angeles. You do not need to be a student at any of these colleges to attend AFROTC on their campuses. For more information, contact the Department of Aerospace Studies at afrotcdet060@rotc.usc.edu or call (213) 740-2670 or visit http://www.usc.edu/afrotc. No military commitment is incurred until entering the junior year of the program or receipt of a scholarship after the freshman year.

The Army ROTC program at USC offers four-, three-, and two-year full-tuition scholarships up to $43,000 a year. In addition, the program pays all contracted cadets a stipend of $3,500 to $5,000 a year and an annual book allowance of another $1200. High-school students need to apply for the four-year scholarship during the fall of their senior year, and no later than November 15. All Caltech students interested in an Army ROTC three- or two-year on-campus scholarship need to apply early in their spring semester, and no later than March 15, for the next academic year. Completion of the program leads to a commission as a Second Lieutenant in one of 14 occupational branches in the Regular Army, Army Reserve, or the National Guard. These scholarship provisions are subject to change, and interested students are encouraged to contact the Department of Military Science at the University of Southern California for further information: PED 110, Los Angeles, CA 90089, (213) 740-1850.

REGISTRATION REGULATIONS

Procedures

Students must register on the dates specified in the academic calendar. Students are not registered until they have both

- enrolled in an approved list of courses, *and*
- are current with the Bursar's Office. All undergraduate students with an outstanding Bursar's bill balance of $300 or more and graduate students with a Bursar's bill balance of $1,500 or more will have a hold placed on their registration for the subsequent quarter the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Any student who has not completed both phases of registration within one week after the first day of classes will be removed from the Institute rolls.

Students are required to maintain continuity of registration until the requirements for the Bachelor of Science degree are fulfilled, except in the case of an approved undergraduate student sabbatical. If continuity is broken by withdrawal, reinstatement is required before academic work may be resumed.

Changes in Registration

All changes in registration must be reported to the Registrar's Office by the student prior to the published deadlines. A grade of F will be given in any course for which a student registers and which he or she does not either complete satisfactorily or drop. A course is considered dropped when a drop card is completed and returned to the Registrar's Office. A student may not at any time withdraw from a course that is required for graduation in his or her option, without permission of the registrar.

A student may not add a course after the last day for adding courses, or withdraw from a course after the last date for dropping courses, without the approval of the Undergraduate Academic Standards and Honors (UASH) Committee. Registration for added courses is complete when an add card, signed by the instructor and the student's adviser, has been filed in the Registrar's Office. No credit will be given for a course for which a student has not properly registered. The responsibility for submitting drop cards and add cards to the Registrar's Office before the deadlines for dropping or adding courses each term rests entirely with the student. Failure to fulfill the responsibility because of oversight or ignorance is not sufficient grounds to petition for permission to drop or add courses after the deadline. It is the policy of the UASH Committee that no petitions for the retroactive dropping or adding of courses will be considered except under very extenuating circumstances.

Humanities Drop Policy
Students who do not attend the first class of the term will be automatically dropped from the class. Students who notify the instructor in advance of their inability to attend the first class may remain enrolled in the class at the instructor's discretion.

Academic Advisement
Students will be assigned freshmen advisers, and later option advisers, who will guide students to resources about the curriculum, graduation requirements, and Institute policies and procedures. Through the academic advising experiences at Caltech, students will develop an educational plan for successfully achieving their goals and select courses each quarter to progress toward fulfilling that educational plan. Undergraduate students are required to meet with their adviser at least once a year. Failure to meet at least once prior to the start of Spring term will result in a hold placed on the student's record which will prevent them from registering online.

Summer Research or Summer Reading

Qualified undergraduate students who are regular students at the Institute are permitted to engage in research or reading during the summer, but in order to receive academic credit the student must have the approval of his or her division and must complete the registration process for such summer work before June 1. An undergraduate may not receive payment for research carried out for academic credit. Students who are registered for summer research or reading will not be required to pay tuition for the units. A student may apply up to 18 units of summer research per summer and 36 units in total toward Institute graduation requirements.

The Institute recognizes that students may want to take advantage of paid internships that provide unique off-campus educational opportunities that integrate and enhance the classroom experience. Students are encouraged to explore and discuss such opportunities with their academic adviser and the dean or associate dean of students. If appropriate, the adviser and dean or associate dean can approve such internships as integral to a Caltech educational experience. There is no academic credit for such work. The internships should commence after the end of the third term and end prior to the resumption of classes in the fall.

Undergraduate Student Sabbatical

An undergraduate student sabbatical must be sought by written petition, which must be accompanied by a completed withdrawal card. The dean or associate dean of students may grant a sabbatical provided (a) the student is in good standing, in other words does not have to meet special academic requirements as a result of reinstatement, (b) the sabbatical is for one year or less, although special circumstances can be considered, and (c) the sabbatical extends over a period that includes at least one full term.

The dean or associate dean may also grant a leave for medical reasons provided the petition is recommended by the senior director of health and counseling services. Return from a leave for medical reasons also requires the recommendation of the senior director of health and counseling services, and the final approval of the dean or the associate dean. A student returning from a leave for medical reasons will maintain the same academic standing that he or she had previously.

Pregnancy Leave
Students who are pregnant are able to take medical leave and return to their studies when appropriate. Pregnancy leave is a form of medical leave and requires students to complete the medical leave petition to leave, and return to, their coursework. If a longer leave is required due to medical complications, students may extend their leave with approval of the undergraduate dean or an associate dean.

Involuntary Leave

Policy Overview
The dean of undergraduate students ("dean") may determine that it is necessary to place a student on an involuntary leave in a variety of circumstances, such as for the protection of the Institute community, for the personal safety or welfare of the student involved, or as a result of a disciplinary action or as an interim measure. The dean may impose an involuntary leave in appropriate circumstances, such as where a student's behavior: (1) has, or threatens to, cause significant property damage; (2) significantly disrupts the functioning of the Institute community; (3) presents a substantial risk of harm to self or others; (4) indicates the student is unable or unwilling to carry out self-care obligations; or (5) violates a Caltech policy or the honor system. An involuntary leave also may be imposed when that the student requires a level of care from the Institute community that exceeds the resources and staffing that the Institute can reasonably be expected to provide for the student's well-being.

Individualized Assessment
When a student's behavior is associated with a physical or mental condition, the dean will conduct an individualized assessment. In making an informed decision to place a student on involuntary leave in such circumstances, the dean will consider relevant medical and/or other information available to him or her, including information provided timely by the student. The dean may consult with the executive director, health and counseling services, or designee, and/or require a physical or mental evaluation from a health professional if the dean believes such an evaluation is necessary in order to make an informed decision. Students are expected, if necessary, to sign a release of information to facilitate discussions between Caltech and the health professional conducting the evaluation. The dean will also consider whether relevant risks factors can be eliminated or reduced to an acceptable level through reasonable accommodation.

Written Decision
The student will be advised in writing of the decision to impose an involuntary leave, any conditions for return, and whether the leave is for a specific term or is indefinite as to term. The dean may stipulate conditions that must be met before the student may return.

Emergency Leave
If the dean determines that a student's continued presence is likely to pose a substantial risk to the safety and well-being of the student or others, the dean may place the student on an emergency interim leave before a final determination is made. The dean will make reasonable attempts to meet with the student and consider relevant information, including medical information provided by the student, before deciding on an interim emergency leave. An emergency leave will remain in effect until a final decision has been made.

While on Leave
A student on involuntary leave may not attend classes, live in Institute housing, participate in Institute programs, or use Institute facilities during the term of the leave, unless approved in writing by the dean.

Return from Leave
A student on involuntary leave will not be allowed to return until the dean makes a fact-specific assessment of the circumstances, considers relevant risk factors, and concludes that the student does not pose a significant disruption to the functioning of the Institute community and/or does not pose a substantial risk to the health and safety of the student or others. The dean will consider relevant information, including information provided by the student. In cases where a student has a physical or mental condition associated with the behavior triggering the leave, the dean will also consider whether the relevant risks can be eliminated by a reasonable accommodation. The student will be notified in writing if the dean determines that the student will not permitted to return from a leave.

Appeal
A decision by the dean of undergraduate students to place a student on involuntary leave or a decision not to permit the student to return from involuntary leave may be appealed in writing within ten days to the vice president for student affairs (or his or her designee).

Withdrawal from the Institute

Formal separation from the Institute is effected by filing a completed withdrawal card in the dean of students office to be forwarded to the registrar and other appropriate offices. The effective date of a withdrawal is entered by the dean or associate dean of students. A student leaving the Institute at any time during the term without filing a formal withdrawal card will not be considered withdrawn. In such a case, any grades reported by the instructors will be recorded on the official transcript, and the grade of F will be recorded for all other courses. A student who withdraws, or is absent for a term (or longer), without an approved undergraduate student sabbatical must petition for reinstatement to return to the Institute. Return from involuntary leave requires approval through the dean of students office. Reinstatement rules are listed under scholastic requirements. If the withdrawal occurs after Add Day of any term, a W (standing for "withdrawn") will be recorded on the student's transcript for all courses in which the student is enrolled. A grade of W is not included in the computation of the student's grade-point average. The record will also indicate whether an undergraduate student sabbatical was granted.

SCHOLASTIC REQUIREMENTS

All undergraduates are required to meet certain scholastic standards as outlined subsequently.

Eligibility for Registration

Following the first two terms, which are taken on a pass-fail basis, freshmen will be ineligible to register if they failed to pass at least 33 units in the previous term. After the first two terms of study, all undergraduate students must complete 33 units with a grade-point average of at least 1.9 in order to remain eligible to register for classes. A student may be excused from the 33- unit eligibility requirement if the requisite petition has been approved, prior to Add Day, by the Dean or Associate Dean of Undergraduate Students. Under exceptional circumstances the deans may waive the requirement that such a petition be approved prior to Add Day, but may do so only once during that student's career at Caltech.

Following their first ineligibility, students are to meet with the dean or associate dean of undergraduate students. The dean may choose to reinstate them, in which case they will be on academic probation. Alternatively, the dean may direct them to petition the Undergraduate Academic Standards and Honors Committee (UASH) for reinstatement. UASH will either approve their petition for reinstatement and place them on academic probation, or require them to withdraw from the Institute for at least two terms. Students who fail a core course or who fail to successfully complete 36 units, even though they remain in good standing, are required to meet with one of the undergraduate deans before being allowed to register for classes in the subsequent term.

Students who becomes ineligible a second time will be required to withdraw from the Institute for at least two terms. Summer does not count as a term. A student who has been required to leave the Institute because of academic ineligibility may, after at least two terms of leave, petition the Undergraduate Academic Standards and Honors (UASH) Committee for reinstatement. The UASH Committee's decision regarding reinstatement will be based largely on whether or not such students have made good use of their time while away from the Institute. Useful activities include being gainfully employed, having an internship, engaging in a significant amount of volunteer work, or successfully completing courses at another college or university. The Committee will also expect that students applying for reinstatement will have completed work in all Caltech classes in which they had received an E or I grade. Any student who becomes ineligible a third time will not be allowed to continue to enroll at Caltech.

Students who are ineligible may petition the UASH Committee to waive any of the rules listed above, but in order to do so they must first obtain permission from two of the following three individuals: the Dean of Undergraduate Students, the chair of the UASH Committee, and the Registrar. Permission to file a waiver petition will be granted only under exceptional circumstances.

Departmental and Option Regulations

Selection of Option

By the middle of the third term, freshmen must notify the Registrar's Office of their selection of an option in engineering, humanities, social sciences, or science to be pursued in subsequent years. Upon the selection of an option, a freshman will be assigned an adviser in that option, whose approval must then be obtained for registration for the following year.

Undergraduate students may request to add an approved minor to their program of study. The request for a minor must be approved by the option representatives of the student's option and proposed minor. A plan must be presented which meets the minimum requirements for both the option and the minor, but the option representatives may impose additional requirements as well. The approved request must be submitted to the registrar before the start of the senior year.

Undergraduate students may be allowed to major in two options for the Bachelor of Science degree. In order to do so the student must present a rationale for the double option and a plan of study leading to completion of the degree in four years. The plan, and any substantive modifications, must be approved by a committee composed of the option representatives of the two options. The plan must meet the minimum requirements for both options as set forth in this catalog, but the committee may impose additional requirements as well. The approved plan should be submitted to the registrar during the sophomore year, but in any case no later than the start of the senior year. The student will then be assigned an adviser by each option. Consult the registrar for appropriate procedures.

Continuing in an Option

Students whose grade-point averages are less than 1.9 at the end of an academic year in a specific group of subjects designated by their department or option may, at the discretion of their department, be refused permission to continue the work of that option. Such disbarment does not prevent the students from continuing in some other option or from taking additional courses to raise their average in their original option. Students without an option will fall under the direct jurisdiction of the dean of students. Students may remain without an option for no more than one year.

Change of Option

An undergraduate in good standing at the Institute shall be permitted to transfer into any option of his or her choice provided he or she has (a) a 1.9 GPA in subjects required for graduation in that option or in a specific group of subjects designated by that option or (b) permission of the option representative or committee. A change of option is effected by obtaining a Change of Option petition from the Registrar's Office. The completed petition must then be signed by the option representative for the new option (who will assign a new adviser), and filed with the Registrar's Office. Institute regulations require that a student who has made normal progress at the Institute be able to change options at any time up to the end of the sophomore year without penalty either as to time until graduation or as to excessive unit requirements in any term.

Term Examinations

Term examinations will be held in all subjects unless the instructor in charge of any subject shall arrange otherwise. No student will be exempt from these examinations. When conflicts exist in a student's schedule, it is the student's responsibility to report the conflict to the instructor in charge of one of the conflicting examinations and make arrangements for another time.

Satisfactory Academic Progress

Eligibility to register is determined by the student's record as of the first day of classes of the term in which registration is sought. A student will be declared ineligible to register if he or she has completed fewer than 33 units with a 1.9 grade point average in the previous term.

Graduation Requirement

To qualify for graduation a student must complete the prescribed work in one of the options with a passing grade in each required subject and with a grade-point average of 1.9. A grade of F in an elective course need not be made up, provided the student has received passing grades in enough other accepted units to satisfy the minimum total requirements of the option.

Tuition for the baccalaureate degree is based on 12 terms of residence regardless of unit load each term or if a student completes graduation requirements a term(s) early. The 12-term tuition requirement is separate from and in addition to any other degree requirements. Students who graduate early will continue to be billed for the 12 terms. Any exceptions must be approved by the Dean of Undergraduate Students and the Vice President for Student Affairs.

Students who are admitted as transfer students or 3/2 students may be granted advanced standing and tuition credit for academic work accepted in transfer to Caltech. However, transfer and 3/2 students must enroll for a minimum of six terms at Caltech.

Candidacy for the Bachelor's Degree
Students must declare their candidacy for the degree of Bachelor of Science to the registrar on or before the first Monday of November preceding the date on which he or she expects to receive the degree. All subjects required for graduation, with the exception of those for which the candidate is registered during the last term of his or her study, must be completed and the grade recorded by the second Monday of May preceding commencement.

Graduation in the Normally Prescribed Time
Any undergraduate student who fails to complete the requirements for graduation at the end of 12 terms must petition the Undergraduate Academic Standards and Honors Committee for approval to register for further work each term.

Requirement for a Second Bachelor of Science Degree
Under exceptional circumstances, a student may be permitted to return to study for a second Bachelor of Science degree. To receive this permission, the student must petition the Curriculum Committee. If the petition is approved, the student must then register for three consecutive terms of additional study, completing in each term at least 36 units, and must meet all the requirements for graduation in the second option. If additional time is needed to complete the degree, the student must also petition the Undergraduate Academic Standards and Honors Committee for an extension. A student admitted for a second Bachelor of Science degree in a particular option may not change to another option without first submitting a new petition to the Curriculum Committee and receiving the explicit approval of that committee.

Excess of or Fewer Than Normal Units (Overloads and Underloads)
An overload is defined as registration for more than 54 units by an upperclassman or more than 51 units by a freshman. Classroom and laboratory courses are to be limited to 45 units for freshmen for the first two terms and the remaining six units should be used for frontier ("pizza") courses, PE, PA, or research. An underload is registration for fewer than 36 units. A student who wishes to carry an overload in any term must obtain the approval of his or her adviser and of the dean or associate dean of students. Petitions for overloads will not be accepted later than the last day for adding classes in any term.

Underloads for freshmen, sophomores, and juniors must be approved by the dean or associate dean. Seniors may take an underload by presenting for the registrar's approval a senior underload petition and a course plan for graduation the following June, provided that the plan does not require an overload in any term. Incoming students who began school in the Fall 2012 or thereafter and underload will not receive a tuition reduction, only a financial aid reduction.

Allowance and Transfer of Credit

Transfer of Credit from Other Institutions

Regularly enrolled students who want to obtain credit for college courses taken elsewhere should obtain the permission of the dean of students and have a copy of the transcript of their work sent to the Registrar's Office. The student should then obtain an Allowance of Credit form from the Registrar's Office and take this, with the transcript, to the representative of the option in which credit is desired. Credit will be granted when this form, with the appropriate signatures, is returned to the office.

Allowance of Credit in the Humanities and Social Sciences

In general, Caltech students should fulfill Caltech course requirements by taking courses at Caltech. Students are expected to have a well-reasoned educational goal for taking classes elsewhere. The only exceptions are transfer students admitted to advanced standing. Credit for comparable work done at other institutions with similar academic standards is not granted automatically.

Students who wish to take courses elsewhere (whether on leave, in the summer, or during the academic year) should consult, *in advance,* with the executive officer for the humanities or the executive officer for the social sciences, or their designees, to minimize any misunderstanding regarding the nature of credit they may receive. Upon completion of the course, the student must obtain an Allowance of Credit form from the registrar, obtain the signed approval of the executive officer, or his or her designee, for transfer credit, and return the completed form to the Registrar's Office. The executive officers are the final authority in the allowance of credit.

Guidelines and specific information about allowance of credit are available from the Division of the Humanities and Social Sciences.

Other Allowances of Credit

Except for transfer credit and credit based on Caltech placement exams upon admission, credit will not be granted for Caltech courses in which the student is not officially enrolled, except in special circumstances by arrangement with the instructor. Such arrangements must be approved by the Curriculum Committee, and the student must petition the Committee before the work is undertaken.

UNDERGRADUATE EXPENSES

For freshmen and transfer students applying for admission, there is a $75 application fee. This fee is nonrefundable.

Housing contracts must be submitted to the assistant director of housing-occupancy by the date specified in the instructions accompanying the contract.

Expense Summary 2015–16

General:

General deposit	$ 100.00[1]
Orientation fee	500.00[1]
Tuition	43,710.00
	$ 44,310.00

[1] *This charge is made only once during residence at the Institute.*

Other:

Student fees	$ 1,680.00
Room (contract price)	7,536.00[2]
Board (5 days/week)	5,835.00
Additional meal allowance (est.)	1,413.00
Books and supplies (est.)	1,323.00
Personal expenses (est.)	1,974.00

[2] *The housing/room rate is calculated based on the weighted average of all available undergraduate on-campus housing options.*

The tuition and fees charge for all students is payable in full before the first day of classes unless the student enrolls in the Direct Cost Three Payment Plan through the Bursar's Office. The fee to enroll in the plan is $25.00 per term. Enrollment in the Direct Cost Three Payment Plan must be completed by August 10, 2015. Fees are subject to change at the discretion of the Institute.

Tuition for the baccalaureate degree is based on 12 terms of residence regardless of unit load each term or if a student completes graduation requirements a term(s) early. The 12 term tuition requirement is separate from and in addition to any other degree requirements. Official study abroad programs listed in the Catalog fulfill one term of the 12 term requirement.

Students who graduate early, prior to 12 terms, will continue to be billed tuition for the full 12 terms. In addition, aid may not be disbursed to a student to cover tuition if they are no longer attending classes.

Refunds and Fees

Refunds and Repayments

For all students, the institutional charges, e.g., tuition and room and board, will be prorated according to the amount of time the student spent in academic attendance before withdrawing from the Institute before the end of the sixth week of the term. These prorated charges will be compared to the payments received on behalf of the student, and the Institute will determine whether the student is entitled to a refund or owes additional funds to Caltech.

For students receiving funds from federal Title IV, from Caltech, and/or from state programs, the Institute will follow federal and other applicable regulations to determine the amount of all program funds the student has earned at the time of withdrawal. In general, the amount of financial aid earned is based on the amount of time the student has spent in academic attendance. If the amount of aid disbursed to the student is greater than the amount the student has earned, unearned funds must be returned. If the amount the student was disbursed is less than the amount the student earned, the student will be eligible to receive a postwithdrawal disbursement.

Determining the Student's Last Date of Attendance or Withdrawal Date: The Office of the Registrar is responsible for obtaining requests for withdrawal from the undergraduate or graduate dean and for processing official withdrawals. In order to calculate the refund or repayment, Caltech will establish the student's withdrawal date. This date is one of the following:

- the date that the student began the withdrawal process prescribed by Caltech;
- the date the student otherwise provided official notification to the registrar (written or oral) of his or her intent to withdraw;
- the midpoint of the academic term if no official notification is provided;
- the date determined by the registrar if there are special circumstances (illness, accident, grievous personal loss); or
- the date the registrar determines the student has not returned from an approved student sabbatical or if the student does not qualify for a sabbatical.

Academically Related Activities that Determine Academic Attendance: The Institute may use the last date of attendance at an academically related activity as the student's withdrawal date. This may occur if a student begins the withdrawal process and then attends an academically related activity after that date. Caltech considers an academically related activity to include the following:

- attendance at a lab
- attendance at a lecture
- completing a quiz and/or test
- participation in a study session
- academic counseling session
- academic advisement session
- turning in a class assignment

Determining the Return of Federal Funds: The Financial Aid Office and/or the Graduate Office will calculate the federal funds that must be returned to the appropriate federal accounts.

If a student withdraws from the Institute prior to the first day of classes for the period of enrollment, Caltech will return 100 percent of the student's federal financial aid in accordance with federal procedures, as well as Caltech and/or state grants or aid.

If a student withdraws any time after the first day of classes for the period of enrollment, the Institute will perform the following:

- Determine the percentage of the payment period that the student completed. If the student completed more than 60 percent of the period, he or she earned 100 percent of the aid for the period. If the student completed 60 percent or less, the percentage of the period completed is the percentage of aid earned. This percentage is determined by dividing the number of days attended in the period of enrollment by the total days in the period.
- Apply the earned percentage to the amount of aid actually disbursed and the amount that could have been disbursed ("earned aid").
- Subtract earned aid from aid that was actually disbursed. This results in the amount of unearned aid to be returned.

The Financial Aid Office and/or the Graduate Office (as appropriate) will allocate the return of funds back to the student aid programs in the following order:

1. Federal Direct Unsubsidized Stafford Loan Program
2. Federal Direct Subsidized Stafford Loan Program
3. Federal Perkins Loan Program
4. Federal Direct PLUS Loan Program
5. Federal Pell Grant Program
6. Federal SEOG Program
7. Other Title IV programs

Any remaining refund will be returned to the other state, institutional, or private student assistance utilized. Federal Work Study is not included in any of these calculations.

Appeals on Refunds: Any questions or problems related to refunds should be directed to the Bursar's Office. For further information on refunds and repayments, contact the Financial Aid Office, the Graduate Office, or the Bursar's Office.

Underloads: Students who register for less than 36 units ("Underload") will not receive a reduction of tuition. Full tuition will be charged to underloading students' accounts, and applicable financial aid will be reduced, in underload situations.

Dropping a Course: Students who are not enrolled full-time as of the last day to add courses will have their aid revised. Generally, students enrolling less than three-fourths time will have an increased work award. Additional information is available in the Financial Aid Office. Also, students who enrolled prior to the 2012–2013 academic year who may be eligible for underloading credit will not receive a prorated discount if the course is dropped after Add Day.

Refund upon Withdrawal: When a student, for whatever reason, withdraws from Caltech during an academic term, a refund of tuition as well as room and board, if applicable, is calculated. The amount of refund is determined by how much of the term has elapsed. If the student is a recipient of student financial assistance, that assistance, if applicable, will be reduced as a result of his or her withdrawal. Recent federal legislation determines the amount of refund for recipients of federal Title IV student assistance. It is the purpose of this section to inform students of the financial implications of withdrawal.

If the student is not a recipient of federal financial aid, the Institute's refund policy returns any refund of tuition or room and board first to the programs from which assistance has been received (i.e., scholarships, Caltech gift assistance). Any amount remaining will then be returned to the student. The non–Title IV portion will be distributed as appropriate, first to outside agencies, as required, then to the Caltech grant, scholarship, or loan, depending on the composition of the aid package. These distributions will occur as credits to the appropriate aid funds and charge(s) to the student's Caltech account.

If the student is the recipient of federal Title IV student assistance, any refund must then be applied first to the federal aid program(s) in the prescribed order listed on page 191.

In the event that a student's disbursed financial aid exceeds the direct costs on the student's personal account, a credit balance will result. Withdrawal will result in the reversal or repayment of the resulting credit balance.

General Deposit

Each new student is required at his or her first registration to make a general deposit of $100, to cover possible loss and/or damage of Institute property. Upon graduation or withdrawal from the Institute, any remaining balance of the deposit will be applied to the student's outstanding balance or refunded if there is no unpaid balance.

Fees for Late Registration

Registration is not complete until the student has enrolled in a program approved by his or her adviser and has paid tuition and other fees. A penalty fee of $50 is assessed for failure to register within five days of the scheduled dates.

Fees for Late Payment

A $50 late penalty may be charged by the Bursar's Office for failure to clear a past-due account at the beginning of instruction.

Honor System Matters

Monies owed to the Institute resulting from a Board of Control decision may be collected through the Bursar's Office, at the request of the dean of students.

Special Fees
Students taking the Summer Field Geology course (Ge 120 ab) should consult with the division about travel and subsistence arrangements and costs.

Unpaid Bills
All bills owed the Institute must be paid when due. Any student whose bills are past due may be refused registration for the following term. All undergraduate students with an outstanding bursar's bill balance of $300 or more will have a hold placed on their registration for the subsequent term the day before online registration opens. The hold will be released once students have paid their bill at the Bursar's Office. Official transcripts and diplomas will not be released until the bursar account is paid in full.

Caltech ID Card Charges
If an undergraduate student owes more than $300, the student's ID card will be deactivated and he or she will be unable to charge any new purchases. Cards will be reactivated once students have paid their bill in full at the Bursar's Office.

FINANCIAL AID

Caltech believes that qualified students who wish to attend the Institute should not be prevented from doing so for financial reasons. Although the Institute expects students and families to finance the cost of education to the fullest extent possible, the Institute will make every effort to assist those who need help, including those whose financial circumstances change during the year.

Demonstrated financial need is the difference between the annual cost of attending Caltech and the amount the student and parents can reasonably be expected to contribute toward those costs. Costs include actual tuition, student fees, room and board, an allowance for meals not covered in the board contract, books and supplies, and personal expenses. For U.S. citizens or eligible noncitizens who reside in the United States, Canada, Mexico, or Guam, costs include a travel allowance designed to (partially) offset the cost of two round-trips from a student's home during the academic year, and a travel allowance based on airfare for two round-trips. Caltech's estimate of a family's ability to contribute is determined annually in accordance with nationally established guidelines.

Eligibility for each type of assistance varies, depending upon the source of funds. Assistance offered by Caltech includes federal, state, and institutional grants, subsidized part-time jobs, and low-interest loans. U.S. citizens or eligible noncitizens (as defined in the Free Application for Federal Student Aid [FAFSA]) may apply for state and federally funded programs. International students may apply for institutionally funded programs.

Students should not wait to be accepted for admission to Caltech before applying for financial aid. With the exception of international students, applications for admission are evaluated separately from requests for financial aid. Students with complete financial aid applications on file will be considered for all applicable types of need-based assistance. A renewal application must be submitted each year. In addition to direct financial assistance, information is available, upon request, about education payment plans and financial-planning resources. (For information on non-need-based scholarships and prizes, starting on page 212.)

All students who believe they will need assistance to attend Caltech are encouraged to submit financial aid applications. The final day to complete a financial aid application or request a loan is one day after the beginning of the registration period for the term following your last term of enrollment for the year. Please use the table below to determine which deadline applies to you.

Last Term of Enrollment in Academic Year 2015-16	Hard Deadline
Fall Term	November 20, 2015
Winter Term	February 26, 2016
Spring Term	May 20, 2016

The Financial Aid Office staff is happy to talk with students and their families at any time to explain the application process, Caltech's computations, and available programs. For further information on the determination of financial need and on application procedures, as well as on financial aid awards and programs, contact the Financial Aid Office, California Institute of Technology, Mail Code 20-90, Pasadena, CA 91125; call (626) 395-6280; or visit the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

How to Apply for Financial Aid

Slightly different procedures and deadlines exist for each category of students applying for financial aid. Detailed descriptions of these procedures and priority due dates for prospective and continuing students may be found on the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

Application Process for Caltech and Federal Financial Aid for Entering Students (U.S. Citizens and Eligible Noncitizens)

The following materials are needed to apply for all financial aid funds administered by the Caltech Financial Aid Office. We realize that you may not have access to your completed 2015 federal income tax information by the priority due dates and ask that you complete the application based on the best estimates available.

CSS/Financial Aid PROFILE Application:
Register for the 2016–17 CSS/Financial Aid PROFILE after October 1, 2015. Designate "California Institute of Technology" as one of the recipients by using Caltech's CSS Code, 4034. Due dates: Applicants must register for the CSS/Financial Aid PROFILE by December 15, 2015. Regular Decision applicants must submit the completed PROFILE application by January 15, 2016.

Note: Early Action applicants must register for the CSS/Financial Aid PROFILE by October 15, 2015, and must submit the completed PROFILE application by November 15, 2015.

Free Application for Federal Student Aid (FAFSA):
The 2016–17 FAFSA will be available on January 1, 2016, at www.fafsa.ed.gov. File the FAFSA and designate "California Institute of Technology" as the recipient by using Caltech's Undergraduate Federal Code Number, 001131. Due date: March 2, 2016.

IRS Data Retrieval:
When completing the FAFSA you will be asked for parent and student tax information, select the option to view and transfer your 2015 Tax Information from the IRS. Please visit the Caltech Financial Aid website for more details. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

Parents' and Students' Federal Income Tax Return:
Parents and students must submit 2015 Federal Income Tax Returns (including all schedules and W-2s) before eligibility for financial aid can be determined. Applicants will be sent an e-mail from the College Board with instructions on how to submit their tax returns using the Institutional Documentation Service (IDOC). Log in to the IDOC site at https://idoc.collegeboard.com/idoc/index.jsp, download and complete the IDOC cover sheet, and submit your 2015 federal income tax return, all schedules, all W-2 forms, and all other required documents directly to the College Board. If you or your parents own corporations, partnerships, or trusts, please include copies of those tax returns (Forms 1041, 1065, 1120, 1120S, K-1). If you or your parent(s) did not and will not file a federal income tax return, please complete the Parent or Student Certification of Nonfiling. Please attach copies of W-2 or 1099 forms (if applicable) to the Parent or Student Certification of Nonfiling. Use the IDOC Cover Sheet to submit this form and all other required documents directly to the College Board along with your IDOC cover sheet. Due date:
Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

Verification Worksheet:
All students and parents must complete and sign the 2016–17 Verification Worksheet, available at http://www.finaid.caltech.edu. Use the IDOC cover sheet to submit the appropriate worksheet directly to the College Board. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

Caltech Supplemental Application:
All students must complete the 2016–17 Caltech Supplemental Application, available at http://www.finaid.caltech.edu. Use the IDOC cover sheet to submit this form directly to the College Board. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

CSS Noncustodial PROFILE Application:
If your parents are divorced, separated, or never married, your noncustodial parent will need to complete the 2016–17 CSS Noncustodial PROFILE Application. After your CSS/Financial Aid PROFILE application is processed, you will receive an e-mail from the College Board with instructions on how to submit this information. Once you have your login information, your noncustodial parent can access the application at http://www.finaid.caltech.edu. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

Child Support Paid Verification Statement:
Complete this form if either of your parents reported paying child support in 2015 on the 2016–17 FAFSA. Use the IDOC Cover Sheet to submit this form directly to the College Board. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

CSS Business/Farm Supplement:
If you or either of your parents is self-employed or owns a business or farm, you will need to submit the 2016–17 CSS Business/Farm Supplement, available at the Caltech Financial Aid Office website. You will receive an e-mail from the College Board with instructions on how to submit this form and other required tax documents using the Institutional Documentation Service (IDOC). Log in to the IDOC

site to get your IDOC cover sheet. Use the IDOC cover sheet to submit this form and all other required documents directly to the College Board. Due date:

Early Action Due Date: March 2, 2016
Regular Action Due Date: March 16, 2016
Continuing Students Due Date: April 20, 2016

Caltech Scholarship Data Form:
Complete the 2016–17 Caltech Scholarship Data Form to be considered for named and endowed scholarships. Entering students will not be issued a Caltech ID number—required for the form—until sometime in June 2016. Due date:

Continuing Students Due Date: April 20, 2016
Freshman Due Date: July 15, 2016

International Applicants
If you are applying for admission as a freshman for the fall of 2016 and are not a citizen or permanent resident of the United States at the time of your application for admission, you will need to refer to the Caltech Financial Aid Office website at http://www.finaid.caltech.edu for instructions for applying for financial aid. International applicants who do not apply for financial aid by published deadlines, or who are denied aid for their first year at Caltech, are not eligible for need-based financial aid for any other academic period while they are undergraduates at the Institute (with the exception of citizens of Canada and Mexico). Those with financial aid offers will be eligible to apply for assistance in subsequent years. All eligible students must reapply for aid each year.

International students are required to complete the CSS/Financial Aid profile. This online application has been modified to collect family income and asset information from international students. Students will need to register for the PROFILE service online at www.collegeboard.com by December 15, 2015, and indicate the college(s) to which they will be applying. (Students can also visit EducationUSA Advising Centers, which are located around the world, to register online.) Students will then receive a personalized PROFILE application at www.collegeboard.com that should be completed and submitted by February 1, 2016. Please refer to the complete application instructions provided on the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

Types of Aid Available

There are three basic categories of financial aid that may be awarded.

1. Grants and scholarships represent "gift aid," which does not need to be repaid. In general, a Caltech scholarship is awarded based on financial need. Caltech named and/or endowed scholarships are considered to be based on need and merit. If you qualify for a state or federal grant, this grant would be included in your financial aid package.

2. Federal Work-Study or Caltech Work-Study represents student employment funds that have been allocated for you to earn during the academic year. Summer Caltech Work-Study represents funds that have been allocated for you to earn during the summer. While a work-study award is not a guarantee of employment, Caltech generally has more opportunities for student employment than it has students interested in working.
3. Low-interest educational loans: Students are generally offered Federal Perkins Loans or Caltech/Institute loans. Students may be awarded Federal Direct Stafford Loans if they request them.

Caltech Scholarships

Awarded to students with demonstrated financial need. Recipients are expected to be enrolled full-time. The named and/or endowed scholarships are also need-based, but many have a merit component. Recipients of named and/or endowed scholarships are often selected after their initial financial aid offer based on scholarship-specific eligibility. These scholarships are almost always used to replace some or all of the recipient's Caltech scholarship. The Financial Aid Office makes every attempt to renew these scholarships, contingent upon the recipients continuing to meet the specific eligibility criteria.

Federal Grants

Federal Pell Grant

Awarded to exceptionally needy undergraduate students who are seeking their first bachelor's degree. Amounts are set by the federal government based on need and enrollment status. In 2015–16, awards ranged from $588 to $5,775 for full-time students; awards for part-time students are set in proportion to their enrollment, i.e., three-quarter time, half-time, less than half-time. Recipients must be in good academic standing.

Federal Supplemental Educational Opportunity Grant

Awarded to undergraduates with demonstrated need who are seeking their first bachelor's degree. Priority goes to full-time Pell Grant recipients. Recipients must be in good academic standing. Awards cannot exceed $4,000 per year.

State Grants

Cal Grant A

Provides tuition and fee assistance to undergraduate California residents seeking their first bachelor's degree. Awarded on the basis of cumulative grade-point average and financial need. Qualifying students can receive up to $9,084, renewable for up to four years. Continuing Cal Grant recipients must maintain good academic standing in addition to financial need. They are not required to resubmit verification of their grade-point average for renewal.

Cal Grant B
Provides a living-allowance stipend and tuition/fee assistance to undergraduate California residents seeking their first bachelor's degree. Awards are based on cumulative grade-point average and high financial need. Recipients are generally from disadvantaged economic or educational backgrounds. Awards for first-year students provide up to $1,656 for books and living expenses. When renewed or applied beyond the first year, awards also include tuition and fee assistance of up to $9,084. Continuing Cal Grant recipients must maintain good academic standing in addition to financial need. They are not required to resubmit verification of their grade-point averages for renewal.

Other State Grants
Other states, such as Pennsylvania, Vermont, and Rhode Island, may offer grant assistance to their residents who plan to attend Caltech. Students are encouraged to contact their respective state post-secondary agencies for specific eligibility and renewal criteria.

Educational Loans

An educational loan is a serious financial obligation and must be repaid. You should carefully consider the repayment obligation before you accept educational loans. Loans can be an invaluable resource for many students and their families in financing a college education. Students can postpone paying a portion of their educational costs until they complete their education or leave school. The repayment period on most loans can extend up to 10 years after graduation or leaving school.

Graduating with educational debt is a fairly common experience for students. At Caltech, however, the average educational indebtedness at graduation is significantly lower than the national average for students attending four-year private and public colleges. Over the last several years, the average for Caltech graduates has been among the lowest in the nation for four-year colleges.

Federal Perkins Loans
Awarded to students based on financial need. The maximum amount an eligible student may borrow is $5,500 per award year if he or she has not successfully completed a program of undergraduate education ($8,000 per year for graduate students). The maximum aggregate amount that may be borrowed is $11,000 for any student who has not yet completed two years of undergraduate work; $27,500 for an undergraduate student who has completed two years of undergraduate work and is pursuing an undergraduate degree; and $60,000 for a graduate student, including loans borrowed as an undergraduate. The aggregate loan limits include only the unpaid principal. Perkins Loans carry an annual interest rate of 5 percent. Interest does not accrue while the borrower is enrolled in school at least half-time, during the grace period (the time before which the borrower must begin or resume repaying a loan), or during authorized deferments. The borrower is responsible for paying the interest that accrues on the loan during repayment or forbearance (a temporary postponement of

payments). Loans are repayable over a period of up to 10 years and have a nine-month initial grace period.

Your monthly payment amount will depend on the size of your debt and the length of your repayment period. The minimum monthly payment is $40.

The William D. Ford Federal Direct Loan Program

This program offers eligible students and parents the opportunity to borrow money directly from the federal government to help pay the cost of attendance at Caltech. The U.S. Department of Education makes loans, through Caltech, directly to students and/or parents. The Institute will use the loan(s) to pay your tuition/fees and other direct charges such as room and board, and give the student any remaining money for indirect costs. Students and/or parents make their repayments directly to the federal government.

Direct loans include

1. The Federal Direct Stafford Loan Program;
2. The Federal Direct Parent PLUS Loan Program;
3. The Federal Direct Graduate PLUS Loan Program; and
4. The Federal Direct Consolidation Loan Program.

Federal Direct Stafford Loan

There are two types of Federal Direct Stafford Loans: subsidized and unsubsidized. The federal government pays the interest on subsidized loans while the borrower is enrolled at least half-time and during authorized periods of deferment. The interest on unsubsidized loans begins to accrue immediately upon disbursement and is generally capitalized (added to the amount borrowed) when the borrower is no longer enrolled at least half-time.

Eligibility for subsidized Stafford Loans is based on financial need as demonstrated by the FAFSA. Students who do not demonstrate sufficient need or whose need is met may borrow unsubsidized Stafford Loans provided their total financial aid, including the Stafford Loan, does not exceed the total estimated cost of attendance.

Dependent undergraduate students (excluding students whose parents cannot borrow Parent PLUS loans) may borrow Stafford Loan amounts not to exceed an annual total of

- $5,500 for first-year students, with no more than $3,500 in subsidized Stafford;
- $6,500 for second-year students, with no more than $4,500 in subsidized Stafford; and
- $7,500 for third- and fourth-year students, with no more than $5,500 in subsidized Stafford.

Independent undergraduate students and dependent undergraduate students whose parents are unable to borrow Parent PLUS loans may borrow additional unsubsidized Stafford Loan amounts not to exceed an annual total of

- $9,500 for first-year students, with no more than $3,500 in subsidized Stafford;

- $10,500 for second-year students, with no more than $4,500 in subsidized Stafford; and
- $12,500 for third- and fourth-year students, with no more than $5,500 in subsidized Stafford.

Graduate students may borrow Stafford Loan unsubsidized amounts not to exceed an annual total of $20,500.

The maximum outstanding total subsidized and unsubsidized Stafford Loan debt is

- $31,000 for dependent undergraduate students, with no more than $23,000 in subsidized Stafford;
- $57,500 for independent undergraduate students (or for dependent undergraduate students whose parents do not qualify for PLUS loans), with no more than $23,000 of this aggregate amount in the form of subsidized loans; and
- $138,500 for graduate students (including loans for undergraduate study), with no more than $65,500 of this aggregate in the form of subsidized loans.

Stafford Loan interest rates:

The interest rate on subsidized and unsubsidized Stafford Loans disbursed for enrollment periods that begin after July 1, 2015 is currently scheduled to be fixed at 4.29% for undergraduate students.

Undergraduate students:

Enrollment Periods Beginning Between	Interest Rates	
	Subsidized	Unsubsidized
July 1, 2015 - June 30, 2016	4.29%	4.29%
July 1, 2014 - June 30, 2015	4.66%	4.66%
July 1, 2013 - June 30, 2014	3.86%	3.86%
July 1, 2011 - June 30, 2013	3.40%	6.80%
July 1, 2010 - June 30, 2011	4.50%	6.80%
July 1, 2009 - June 30, 2010	5.60%	6.80%
July 1, 2008 - June 30, 2009	6.00%	6.80%

Graduate students:

Enrollment Periods Beginning Between	Interest Rates
	Unsubsidized
July 1, 2015 - June 30, 2016	5.84%
July 1, 2014 - June 30, 2015	6.21%
July 1, 2013 - June 30, 2014	5.41%
July 1, 2006 - June 30, 2013	6.80%

To offset the federal government's cost of the program, the borrower must pay an up-front origination fee of the principal amount of the loan.

First Disbursement Made	Loan Fee
October 1, 2015 – September 30, 2016	1.068%
October 1, 2014 – September 30, 2015	1.073%
December 1, 2013 – September 30, 2014	1.072%
July 1, 2013 – November 30, 2013	1.051%

The maximum repayment period under this program is 10 years, not including authorized periods of deferment. Direct Stafford Loans have a six-month grace period that starts the day after the borrower graduates, leaves school, or drops below half-time enrollment. Repayment begins when the grace period ends. Deferments are available for new borrowers during at least half-time enrollment at an eligible institution; during periods of academic study in approved graduate fellowship or rehabilitation programs; and for periods of unemployment and economic hardship.

Applications for Federal Direct Stafford Loans are available on the Caltech Financial Aid Office website. Complete information on Stafford Loan deferments and repayment options is also available from the Financial Aid Office.

Federal Parent PLUS Loan

Parent PLUS loans are available to the parents or stepparents of dependent undergraduate students. These credit-based loans are not based on federal need or subsidized by the government, but students must file a FAFSA in order for their parents to qualify for a Parent PLUS loan.

Enrollment Periods Beginning Between	Interest Rates
July 1, 2015 - June 30, 2016	6.84%
July 1, 2014 - June 30, 2015	7.21%
July 1, 2013 - June 30, 2014	6.41%
July 1, 2006 - June 30, 2013	7.90%

Interest is charged on Direct Parent PLUS loans during all periods, beginning on the date of the loan's first disbursement. There is no annual limit to the amount that can be borrowed through the Parent PLUS loan program. In general, parents may borrow the difference between the cost of the student's education and any other financial aid received. PLUS loans may also be used to pay for all or part of the expected family contribution. In addition to the interest, parents pay a loan fee. For all loans originated before July 1, 2013 there is a 4.0% origination fee assessment per loan.

First Disbursement Made	Loan Fee
October 1, 2015 – September 30, 2016	4.272%
October 1, 2014 – September 30, 2015	4.292%
December 1, 2013 – September 30, 2014	4.288%
July 1, 2013 – November 30, 2013	4.204%

For Parent PLUS loans that are first disbursed on or after July 1, 2008, parent borrowers have the option of deferring repayment based on the enrollment status of the dependent student on whose behalf a Direct PLUS loan was obtained.

Specifically, Parent PLUS loan borrowers may defer repayment

- while the dependent student on whose behalf the loan was obtained is enrolled on at least a half-time basis, and
- during the six-month period after the dependent student on whose behalf the loan was obtained ceases to be enrolled on at least a half-time basis.

If a Parent PLUS loan borrower does not request a deferment, the first payment on the loan will be due within 60 days after the loan is fully disbursed.

Applications for Federal Direct Parent PLUS loans are available on the Caltech Financial Aid Office website. Applications must be submitted to the Financial Aid Office for eligibility certification. Complete information on Parent PLUS loan deferments and repayment options is also available from the Financial Aid Office.

Federal Student Aid Ombudsman

The Federal Student Aid Ombudsman works with student loan borrowers to informally resolve loan disputes and problems. The office of the ombudsman helps borrowers having problems with the following federal loans: direct loans (subsidized and unsubsidized Direct Stafford Loans, Direct PLUS loans, and Direct Consolidation Loans); Federal Family Education Loans (subsidized and unsubsidized Stafford Loans, FFEL PLUS loans, and FFEL Consolidation Loans); guaranteed student loans, SLS loans, and Federal Perkins Loans. If a student needs the assistance of the ombudsman in order to resolve disputes or problems, he or she may contact the office at U.S. Department of Education, FSA Ombudsman, 830 First St., NE, Mail Stop 5144, Washington D.C. 20202-5144; (202) 275-0549 or (877) 557-2575; fsaombudsmanoffice@ed.gov; or visit the website at http://www.ombudsman.ed.gov.

Caltech Loans

Awarded to students who are not eligible for or who may have used their eligibility for Federal Perkins Loans. Generally, no interest is charged and no repayment of principal is required while a student maintains a continuous course of study at Caltech. Like the Federal

Perkins Loan program, repayment on Caltech loans begins nine months after graduation, leaving school, or less than half-time enrollment. Caltech loans carry an annual interest rate of 5 percent. More specific information is provided on the promissory note and the disclosure statement provided to students prior to disbursement of the loan.

Other loans/emergency loans may be available to students regardless of their eligibility for financial aid. These loans are usually payable within the same academic year and are administered by the dean of students on a case-by-case basis. Additional information and applications may be obtained from the dean of students office.

The Caltech Y also has a no-interest, 30-day emergency-loan program. Maximum loans are $50. Additional information and applications may be obtained from the Caltech Y.

Student Employment

Work programs provide students with the opportunity to earn money to help with college expenses while gaining valuable job experience. Student employment opportunities are generally available to all Caltech students, even those who have not applied for financial aid or qualified for need-based aid. Students should go to the Career Development Center website to see relevant job listings. Note that students may not work more than 16 hours per week. First-year students may not work during fall term.

Students can expect to earn at least the California state minimum wage of $9 per hour. Compensation rates will vary based on the position, a student's skills, and previous work experience. Please note that undergraduate students who serve as teaching assistants may only have one assignment per term of up to 12 hours per week.

Federal Work-Study

Awarded to domestic students who have demonstrated financial need through their submission of the FAFSA, this federally funded program provides part-time employment to eligible students.

Most Caltech students are awarded $2,500 in Federal Work-Study (FWS). Some students may be awarded less. Since entering students are not permitted to work on-campus in the fall term and can only work in the winter and spring terms, student employment awards for entering students are limited to $1,350 in their first year. Employment awards will increase to the standard student employment amount offered to continuing students after the first year. The maximum amount of FWS wages that a student may earn is determined by his or her financial need. Students have the option to move all or a portion of their loan or student employment from one program to the other at any time during the academic year. The final day to request to convert your loan into work or work into loan is one day after the beginning of the registration period for the term following your last term of enrollment for the year. Please use the table below to determine which deadline applies to you.

Last Term of Enrollment in Academic Year 2015-16	Hard Deadline
Fall Term	November 20, 2015
Winter Term	February 26, 2016
Spring Term	May 20, 2016

Please go to the work-study page on the Caltech Financial Aid Office website (http://www.finaid.caltech.edu/workstudy) for additional information about student employment at Caltech.

Caltech Work-Study

The Caltech Work-Study Program is funded by the Institute and is designed to provide part-time employment for international students who have demonstrated financial need, and other students who do not qualify for the Federal Work-Study Program. The Caltech Work-Study Program is limited to on-campus employment or student employment positions at the Jet Propulsion Laboratory. The program's regulations parallel the Federal Work-Study Program's regulations.

Financial Aid When Studying Abroad

Caltech provides student financial aid (in the form of grants, scholarships, and loans) to those undergraduates with demonstrated financial need who desire to participate in the Institute-sponsored Caltech Cambridge Scholars Program, Caltech Copenhagen Scholars Program, Caltech Edinburgh Scholars Program, École Polytechnique Scholars Program, Caltech London Scholars Program, or Melbourne Scholars Program. Enrollment in a study-abroad program approved for credit by Caltech will be considered enrollment at the Institute, for the purpose of applying for and receiving federal student financial assistance. To be eligible for consideration in Caltech's study-abroad programs, students must be in good academic standing, as defined in the *Caltech Catalog* and as certified by the Institute's registrar. They must also meet the minimum GPA requirement as outlined in the information provided by the Fellowships Advising and Study Abroad Office. In addition, students selected to be Cambridge, Copenhagen, École Polytechnique, Melbourne, or University College London scholars will be provided a memo of understanding outlining the terms of their study-abroad participation. (For more information on study abroad, see page 172.)

Costs include but are not limited to tuition, fees, room, board, additional meals not covered by a board contract, books, supplies, personal expenses, and a standard transportation allowance from the student's home to Caltech. Transportation expenses related to the student's travel between Caltech and the study-abroad institution are the responsibility of the student; financial aid recipients may be offered interest-free Institute loans to cover study-abroad travel expenses. Students will have their expected family contribution and financial package calculated in the same manner as other students. Students studying abroad are subject to the standard Caltech policy of a maximum of 12 terms of eligibility for financial aid. Cambridge, Copenhagen, University College London, École Polytechnique, University of Edinburgh, and Melbourne University candidates must meet all financial aid priority deadlines and eligibility requirements to receive aid. It is the student's responsibility to ensure that all necessary documents are filed and complete with regard to their application for financial aid. Cambridge, Copenhagen, University College London, École Polytechnique, University of Edinburgh, and University of Melbourne scholars will continue to be considered for available federal, state, Caltech grant, scholarship, and loan funds. The Fellowships Advising and Study Abroad Office will make the necessary arrangements with the Bursar's Office to ensure that scholars who may be eligible for funds in excess of the direct charges to the Institute receive those funds prior to their departure.

Other Resources

A number of both local and national organizations offer outside scholarships to continuing students throughout the year, some of these regardless of need. The student newspaper, the *California Tech*, announces eligibility criteria for several such scholarships. Those relevant to undergraduate students will also be posted in the Scholarship News section of the Caltech Financial Aid Office website. Such scholarships can also often be found with the help of a search service. We recommend FastWeb (www.fastweb.com); College Board Fund Finder (https://bigfuture.collegeboard.com); CollegeNet/MACH25 http://www.collegenet.com/mach25/app; and nerdscholar http://www.nerdwallet.com/nerdscholar/scholarships/. (For more information on scholarship services, go to www.finaid.org.)

Outside scholarships acquired by students are considered, by federal regulation, to be a resource available during the academic year. Caltech's policy is to use outside scholarships to replace the student employment and/or loan components of the financial aid package. For entering students, we generally replace student employment first. For continuing students, loans are generally replaced first. Only if the total outside scholarships exceeds the student employment and/or loan that would have been included in your financial aid package will it be necessary to reduce Caltech scholarship. In general, a student's total financial aid, including outside assistance, cannot exceed his or her demonstrated financial need. Under no circumstances can a student's total financial aid, exceed their estimated cost of attendance.

Financial Aid Disbursement

Most financial aid funds are credited directly to your student account and are applied first to institutional charges for the current term. Funds are credited no earlier than 10 days prior to the first day of the term. Aid that can be credited directly to your account will be credited when you have

- accepted or declined your awards on access.caltech;
- provided all required documents for the aid programs you have been awarded;
- made satisfactory academic progress;
- enrolled in at least the minimum number of credits for the financial aid programs you have been awarded;
- completed all necessary loan documents and, for first-time Direct Stafford Loan borrowers, completed the online Entrance Interview.

If the disbursement of your aid results in a credit balance, any aid awarded in excess of institutional charges will be paid to the student as a refund. Refunds must be requested by the account holder. Requests may be made by e-mail, telephone, or in person at the Bursar's Office. Prior to receiving funds, it may be necessary to fill out and sign a refund form. Refunds can be obtained in cash or by check. A maximum refund of $500 cash per day can be received from the Bursar's Office cashier. Refund checks are requested by the Bursar's Office and issued by Accounts Payable. This usually takes five working days from the day of request.

Outside scholarships are usually disbursed in the form of a check and must be handled according to the sponsor's specifications. If the funds are sent to the Financial Aid Office or the Bursar's Office, they will be credited to your account. Again, if the crediting of any outside scholarship results in a credit balance on your account, you may request that the credit balance be refunded to you. Federal regulations allow Caltech to credit financial aid funds to your account for payment of tuition, fees, and room and board charges. You must give the Bursar's Office written authorization to keep a credit balance on your account from one term to the next term during the academic year. Federal guidelines prohibit keeping a credit balance from one academic year to the next. If you complete your financial aid file late in the term, resulting in the late disbursement of your financial aid funds, you may be subject to late fees assessed by the Bursar's Office.

Cal Grant B stipend payments will be credited to your tuition account unless you contact the Financial Aid Office in person within the first three weeks of the term to make alternate arrangements. Again, if the crediting of any financial aid results in a credit balance on your account, you may request that the credit balance be refunded to you.

In general, loans are disbursed in three installments, one at the beginning each term. For most Caltech students who are enrolled for the full academic year, this means that one-third of their loan(s) will be disbursed at the beginning of the fall term, another at the beginning of the winter term, and the final third at the beginning of the spring term. Students whose loan periods are for one term receive their entire disbursement at the beginning of that term.

If you work through either the Federal Work-Study or the Caltech Work-Study program, you will be paid by check through the biweekly Caltech payroll system. Checks are normally distributed at your actual work site.

Since financial aid is generally awarded on the assumption of full-time enrollment, it is possible that some or all of your aid will need to be adjusted if your enrollment status results in a reduction in your tuition for a term. If you withdraw or drop below half-time enrollment after the last day for adding classes for a term, you may be required to repay all or a portion of the aid that has already been credited to your account. You must inform the Financial Aid Office if you take a leave of absence or change your enrollment subsequent to receiving your financial aid. Cal Grant recipients who take a leave of absence are advised to contact the California Student Aid Commission (www.csac.ca.gov) and submit a form to remain eligible for the program.

You have the right to cancel your loan(s) anytime before disbursement and up to 14 days after disbursement.

Satisfactory Academic Progress (SAP)

Federal and state regulations governing student financial aid programs require the institute to ensure that each student who is receiving financial aid maintains Satisfactory Academic Progress (SAP) toward his or her degree.

The SAP check occurs after grades are posted at the end of each term. Failure to meet the standards of satisfactory academic progress may disqualify a student from enrollment at the Institute and/or additional federal, state, and institutional financial aid. A student who successfully appeals their ineligibility for registration will be placed on warning, probation or continued on probation status for financial aid purposes.

Academic Requirements

Following the first two terms, which are taken on a pass-fail basis, freshmen will be ineligible to register if they failed to pass at least 33 units in the previous term. After the first two terms of study, all undergraduate students must complete 33 units with a grade-point average of at least 1.9 in order to remain eligible to register for classes. A student may be excused from the 33- unit eligibility requirement if the requisite petition has been approved, prior to Add Day, by the Dean or Associate Dean of Undergraduate Students. Under exceptional circumstances the deans may waive the requirement that such a petition be approved prior to Add Day, but may do so only once during that student's career at Caltech.

Following their first ineligibility, students are to meet with the dean or associate dean of undergraduate students. The dean may choose to reinstate them, in which case they will be on academic probation. Alternatively, the dean may direct them to petition the Undergraduate Academic Standards and Honors Committee (UASH) for reinstatement. UASH will either approve their petition for reinstatement and place them on academic probation, or require them to withdraw from the Institute for at least two terms. Students who fail a core course or who fail to successfully complete 36 units, even though they remain in good standing, are required to meet with one of the undergraduate deans before being allowed to register for classes in the subsequent term.

Students who become ineligible a second time will be required to withdraw from the Institute for at least two terms. Summer does not count as a term. A student who has been required to leave the Institute because of academic ineligibility may, after at least two terms of leave, petition the Undergraduate Academic Standards and Honors (UASH) Committee for reinstatement. The UASH Committee's decision regarding reinstatement will be based largely on whether or not such students have made good use of their time while away from the Institute. Useful activities include being gainfully employed, having an internship, engaging in a significant amount of volunteer work, or successfully completing courses at another college or university. The Committee will also expect that students applying for reinstatement will have completed work in all Caltech classes in which they had received an E or I grade.

Any student who becomes ineligible a third time will not be allowed to continue to enroll at Caltech.

Students who are ineligible may petition the UASH Committee to waive any of the rules listed above, but in order to do so they must first obtain permission from two of the following three individuals: the Dean of Undergraduate Students, the chair of the UASH Committee, and the Registrar. Permission to file a waiver petition will be granted only under exceptional circumstances.

Financial Aid Warning

Students who are found not to be making satisfactory academic progress at the end of an academic term will be ineligible to register. For the first such ineligibility, the petition may be acted on by the dean or associate dean of undergraduate students, after consultation with the student and examination of the record. At the dean's discretion, such cases may be referred to the UASH Committee for action. If given permission to register, students will be on academic probation and will be placed on financial aid warning. A student may continue to receive financial aid for one term while on financial aid warning status. Students should use this opportunity to re-establish SAP.

Financial Aid Probation

Students who fail to make satisfactory academic progress after their term of financial aid warning will be ineligible to register, ineligible for financial aid, and will be required to withdraw from the Institute for at least two terms. Students may appeal this status as outlined in the Academic Requirements above.

Undergraduate students may, after at least two terms of leave, petition the UASH Committee for reinstatement. Students who are reinstated as a result of their appeal/petition for reinstatement will be placed on financial aid probation and may receive financial aid for an additional academic term.

As stated above, students who fail to make satisfactory academic progress for a third time will not be allowed to continue their enrollment at the Institute.

Continued on Financial Aid Probation

Students who fail to make satisfactory academic progress while on financial aid probation but are reinstated as a result of a UASH petition will be continued on financial aid probation and be ineligible for federal and state aid.

A student who is continued on financial aid probation and again fails to make satisfactory academic progress would almost certainly not be allowed to continue their enrollment. If, however, they successfully petition the UASH Committee for reinstatement, they would be continued on financial aid probation for a second term. Technically, a student may be continued on financial aid probation for up to three consecutive terms but their scholarship eligibility will be reduced in each of those terms.

Financial Aid Suspension

Students who fail to make satisfactory academic progress after being continued on financial aid probation for three consecutive terms and are again reinstated by the UASH Committee will be ineligible for federal, state, and institutional financial aid at Caltech until such time as they make satisfactory academic progress.

Maximum Time Frame for Receiving Aid

A student has a limited time frame to complete all degree requirements and remain eligible for financial aid. As defined by federal regulations, the maximum time frame is 150 percent of the published program length for degree completion.

To qualify for a Bachelor of Science degree, students must complete a minimum of 486 units (515 units for chemical engineering) 486 x 150% = 729 maximum attempted units (515 x 150% = 772 maximum attempted units for chemical engineering)

An “attempted” unit is defined as any unit that a student remains enrolled in AFTER the Add Period, including units the student withdraws from each term. Units that a student is retroactively enrolled in after the Add Period are considered attempted units.

Class Level for Financial Aid Purposes

Undergraduate students are classified according to the number of units earned and the number of terms in residence at Caltech. Both these criteria must be satisfied for class-level eligibility. Students are regarded as freshmen until eligible for sophomore status, and as sophomores, juniors, or seniors if they meet the corresponding criteria set below.

Units earned are defined as units completed with a passing grade.

Classification	*Minimum Units Earned*	*Minimum Terms in Residence*
Sophomore	108	3
Junior	216	6
Senior	324	9

Part-Time Enrollment (Underloads)

Starting with the undergraduate cohort entering Fall 2012, undergraduate students who underload in a term will be charged full-time tuition but their financial aid, including outside scholarships, will be adjusted as indicated on the Financial Aid Website based on the actual number of units students are enrolled in as of Add Day. The Institute will charge students for a minimum of 12 terms of full-time tuition, or the prorated equivalent based on their classification at the time they begin their enrollment, even if they complete their degree requirements early. Students may NOT receive scholarship assistance for any term in which they are not enrolled at least half-time. Students may petition the Dean of Students Office for exceptions to the tuition policy, NOT the financial aid policy.

Underloads

Underloads and Financial Aid: The Impact of Less than Full-time Enrollment

Any student who wishes to carry fewer than 36 units in any given term must petition for an underload. Underloads must be approved by the Dean of Students Office. Underloads for graduating seniors must be approved by the Registrar. Petitions are available online and in the Deans' Office Students enrolled half-time (taking 18 to 26 units) will be expected to work additional hours during the academic year, as well as to accept a reduction in the tuition, books and supplies allowance of their college expense budget. The following information summarizes the impact of less than full-time enrollment.

3/4 Time

Full-time enrollment is defined in the Caltech Catalog as 36 units. Students enrolling less than full-time, taking between 27 to 35 units, are considered enrolled 3/4 time. The impact to their financial aid is usually a reduction to their grant, in the same amount as the reduction in their tuition. Federal Pell Grant recipients will have their Federal Pell award reduced according to federal regulations. The Financial Aid Office will revise the student's budget for financial aid purposes to reflect the reduction in tuition charged and then revise the student's aid (grant eligibility) to reflect the reduction in need.

1/2 Time
Half-time enrollment is defined as enrolling in 18 to 26 units. In this situation, the Financial Aid Office will revise the tuition amount on the budget for financial aid purposes and also reduce the student's books and supplies allowance to one half of the standard amount for that term. The student's aid is adjusted to reflect the reduced financial aid eligibility. Federal Pell Grant recipients will have their Pell award reduced according to federal regulations. The Financial Aid Office will revise the student's budget for financial aid purposes and then revise the student's aid (grant eligibility) to reflect the reduction in need.

Less than 1/2 Time
Less than 1/2 time enrollment is defined as taking fewer than 18 units. Tuition is revised for financial aid purposes. As indicated in the Caltech Catalog, the minimum tuition charge is 10 units per term. The books and supplies allowance is reduced to 1/4 for that term. The student's aid is reduced based on the reduced costs. Federal Pell Grant recipients will have their Pell award reduced according to federal regulations. More importantly, the student becomes ineligible for Caltech grant aid for that term; the student will only be eligible for Caltech work study and loan assistance. If the student is enrolled less than half time, the grace period on any student loan (Federal Perkins loan, CIT loan, Institute loan and Federal Stafford loan) will begin. In addition, a student/family is no longer eligible for Federal PLUS or Stafford loans during periods of less than 1/2 time enrollment.

Effect on Outside Scholarships
In all of the above categories, the Financial Aid Office also checks to see if a student has an outside scholarship that requires continuous full-time enrollment. If a scholarship donor requires full time enrollment, the Financial Aid Office is required to return the scholarship money for that term to the donor. If this occurs, the student is encouraged to contact the donor directly to review and, possibly, appeal the agency's policy.

Questions
Students with questions regarding underloads should discuss their individual circumstances with a Financial Aid Counselor.

PRIZES

Tom Apostol Award for Excellence in Teaching in Mathematics
In 2010, the mathematics option set up the Apostol Teaching Award named in honor of Tom Apostol, who was a great teacher at Caltech for over 50 years. The three to five awards are given each year to recognize excellence in teaching by mathematics graduate and undergraduate teaching assistants.

Robert P. Balles Caltech Mathematics Scholars Award
An annual prize is awarded to the mathematics major entering his or her senior year who has demonstrated the most outstanding performance in mathematics courses completed in the student's first three years at Caltech. The executive officer for mathematics, in consultation with the faculty, determines the recipient. The prize is made possible by a gift from Mr. Robert P. Balles.

Mabel Beckman Prize
The Mabel Beckman Prize is given in memory of Mrs. Beckman's many years of commitment to Caltech's educational and research programs. The prize is awarded to an undergraduate woman who, upon completion of her junior or senior year at Caltech, has achieved academic excellence and demonstrated outstanding leadership skills, a commitment to personal excellence, good character, and a strong interest in the Caltech community. This prize is given at commencement.

Eric Temple Bell Undergraduate Mathematics Research Prize
In 1963 the department of mathematics established an undergraduate mathematics research prize honoring the memory of Professor Eric Temple Bell, and his long and illustrious career as a research mathematician, teacher, author, and scholar. His writings on the lives and achievements of the great mathematicians continue to inspire many hundreds of students at Caltech and elsewhere. A prize is awarded annually to one or more juniors or seniors for outstanding original research in mathematics, the winners being selected by members of the mathematics faculty. The funds for this prize come from winnings accumulated over the years by Caltech undergraduate teams competing in the William Lowell Putnam Mathematics Contest, an annual nationwide competition.

Bhansali Prize in Computer Science
The Bhansali Prize was established in 2001 by Vineer Bhansali (B.S. '87, M.S. '87) in memory of his grandfather, Mag Raj Bhansali. The prize and honorarium are awarded to an undergraduate student for outstanding research in computer science in the current academic year. Awardees are selected by a committee of computer science faculty.

Amasa Bishop Summer Study Abroad Prize
This prize is awarded to one or more freshmen, sophomores, or juniors to fund summer study abroad in an organized program with the aim of gaining exposure to foreign language and international issues or cultures, including global issues in the sciences and engineering.

Marcella and Joel Bonsall Prize for Technical Writing
The Marcella and Joel Bonsall Prize for Technical Writing was established by the late Marcella Bonsall to encourage SURF students to develop excellent technical writing skills. Mentors

may nominate their students' papers for consideration. A faculty committee recommends the winning papers. Up to five prizes may be awarded annually.

Richard G. Brewer Prize in Physics
The Richard G. Brewer Prize is awarded to the freshman with the most interesting solutions to the Physics 11 "hurdles," in recognition of demonstrated outstanding intellectual promise and creativity at the very beginning of his or her Caltech education.

The award is a stipend that will support the student for the summer while he or she works on an independent Physics 11 project. This award is made possible by a gift from Dr. Richard G. Brewer, a Caltech alumnus who received his B.S. degree in chemistry in 1951.

Fritz B. Burns Prize in Geology
This prize is awarded to an undergraduate who has demonstrated both academic excellence and great promise of future contributions in the fields represented by the Division of Geological and Planetary Sciences.

Bonnie Cashin Prize for Imaginative Thinking
This prize, established in 1997 by Bonnie Cashin, is awarded each year to the entering freshman who has written the most imaginative essays in the Application for Freshman Admission. The Freshman Admissions Committee will nominate awardees to the vice provost, who will approve the selection. The award may be shared if there is more than one deserving student in a particular year.

Donald S. Clark Memorial Awards
From a fund contributed by the Caltech Alumni Association, annual awards are made to two juniors in engineering options. The award recognizes service to the campus community and a grade-point average equal to or greater than that required for graduation with honor. The awards honor the work of Professor Clark, class of 1929, both in the field of engineering and in his service to the Alumni Association.

Deans' Cup and Student Life and Master's Award
Two or more awards are presented to undergraduates whose concern for their fellow students has been demonstrated by persistent efforts to improve the quality of undergraduate life and by effective communication with members of the faculty and administration.

Doris Everhart Service Award
The Doris Everhart Service Award is given annually to an undergraduate who has actively supported and willingly worked for organizations that enrich not only student life, but also the campus and/or community as a whole, and who has, in addition, exhibited

care and concern for the welfare of students on a personal basis. The award was made possible by Sally V. Ridge and was established to honor Doris Everhart.

Richard P. Feynman Prize in Theoretical Physics
This prize was established through gifts in memory of Richard P. Feynman and the senior class gift of the class of 1989. It is awarded annually to a senior student on the basis of excellence in theoretical physics. The prize consists of a cash award and a copy of the three-volume set *The Feynman Lectures on Physics*.

Haren Lee Fisher Memorial Award in Junior Physics
Mr. and Mrs. Colman Fisher established the Haren Lee Fisher Memorial Award in Junior Physics in memory of their son. The General Electric Foundation also contributed to the fund under the matching plan of their Corporate Alumnus Program. A prize will be awarded annually to a junior physics major, who is selected by a physics faculty committee as demonstrating the greatest promise of future contributions to physics.

Henry Ford II Scholar Awards
Henry Ford II Scholar Awards are funded under an endowment provided by the Ford Motor Company Fund, a nonprofit organization supported primarily by contributions from the Ford Motor Company. Each award will be made annually either to the engineering student with the best academic record at the end of the third year of undergraduate study, or to the engineering student with the best first-year record in the graduate program. The chair of the Division of Engineering and Applied Science names the recipient.

Jack E. Froehlich Memorial Award
The family and friends of the late Jack E. Froehlich, who did his undergraduate and graduate work at Caltech and was later the project manager for Explorer I for the Jet Propulsion Laboratory, established a prize fund that provides an award to a junior in the upper five percent of his or her class who shows outstanding promise for a creative professional career. The student is selected by the deans and the Undergraduate Academic Standards and Honors Committee.

George W. and Bernice E. Green Memorial Prize
The George W. and Bernice E. Green Memorial Prize was established in 1963 with contributions given in memory of George W. Green, who for 15 years served on the staff of the Caltech business office and was vice president for business affairs from 1956 to 1962. The prize is awarded annually to an undergraduate student in any class for original research, an original paper or essay, or other evidence of creative scholarship beyond the normal requirements of specific courses. The student is selected by the deans and the Undergraduate Academic Standards and Honors Committee.

David M. Grether Prize in Social Science
The prize rewards outstanding performance and creativity by a Caltech undergraduate who completes one of the social science options. The prize is funded by Susan G. Davis in recognition of David M. Grether's contributions to econometrics and experimental economics and his service to the Division of the Humanities and Social Sciences. The prize is awarded annually by a committee of social science faculty.

Lucy Guernsey Service Award
Awarded to one or two students who have provided exceptional service to the Caltech Y and/or the community, are involved with service projects, have demonstrated leadership in community and volunteer service efforts, and who exemplify a spirit of service. Established by the Caltech Y ExComm in honor of Lucy Guernsey, the Y's executive director from 1989 to 1991.

Arie J. Haagen-Smit Memorial Fund
The Arie J. Haagen-Smit Memorial Award was established in 1977 to honor the memory of the pioneering bioorganic chemist who discovered the chemical constituents of smog. Dr. Haagen-Smit was a member of the Caltech faculty for 40 years, and his family and friends have arranged for a prize to be given at the end of the sophomore or junior year to a student in biology or chemistry who has shown academic promise and who has made recognized contributions to Caltech. The selection is made by faculty representatives from the biology and chemistry divisions, and the deans.

Frederic W. Hinrichs, Jr., Memorial Award
The Board of Trustees of the California Institute of Technology established the Frederic W. Hinrichs, Jr., Memorial Award in memory of the man who served for more than 20 years as dean and professor at the Institute. In remembrance of his honor, courage, and kindness, the award bearing his name is made annually to the senior who throughout his or her undergraduate years at the Institute has made the greatest contribution to the student body and whose qualities of character, leadership, and responsibility have been outstanding. At the discretion of the deans, more than one award, or none, may be made in any year. This award is given at commencement.

Alexander P. and Adelaide F. Hixon Prize for Writing
The Hixon Prize for Writing was established in 2000 by Alexander P. and Adelaide F. Hixon. The prize will be awarded annually to an undergraduate student for the best composition in a freshman humanities course. The prize is administered by the writing center, and the winner will be chosen by a committee from the humani-ties division.

The George W. Housner Prize for Academic Excellence and Original Research
The George W. Housner prize is given annually to a senior in the upper 20 percent of his or her class who has demonstrated excellence in scholarship and in the preparation of an outstanding piece of original scientific research. The student is selected by the deans and the Undergraduate Academic Standards and Honors Committee. At the discretion of the dean, more than one award may be made in any year. The prize, presented at commencement, consists of a cash award and a certificate. This prize is made possible by a gift from George W. Housner, Carl F Braun Professor of Engineering, Emeritus.

Bibi Jentoft-Nilsen Memorial Award
Family and friends of Bibi Jentoft-Nilsen, class of 1989, have provided this award in her memory. This cash award is for an upperclass student who exhibits outstanding qualities of leadership and who actively contributes to the quality of student life at Caltech.

Scott Russell Johnson Undergraduate Mathematics Prize
This prize is awarded to the best graduating mathematics major. The prize may be split between two students. In deciding on the winner, special consideration will be given to independent research done as a senior thesis or SURF project. The executive officer for mathematics, in consultation with the faculty, determines the recipient. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

D. S. Kothari Prize in Physics
This prize was established in 1998 in memory of Dr. D. S. Kothari, who received his Ph.D. under Lord Rutherford in 1933, and subsequently made significant contributions in theoretical astrophysics and science education. The award is given each year to a graduating senior in physics who has produced an outstanding research project during the past year.

Margie Lauritsen Leighton Prize
From a fund established by Dr. Fay Ajzenberg-Selove and Dr. Walter Selove, the departments of physics and astrophysics will annually award the Margie Lauritsen Leighton Prize to one or two undergraduate women who are majoring in physics or astrophysics, and who have demonstrated academic excellence. The prize consists of a cash award and will be made at the end of the sophomore year.

Mechanical Engineering Award
Awarded to a candidate for the degree of Bachelor of Science in mechanical engineering whose academic performance has demonstrated outstanding original thinking and creativity as judged by a faculty committee appointed each year by the Executive Officer for Mechanical Engineering. The prize consists of a citation and a cash award.

James Michelin Scholarship
Given in memory of geologist James Michelin, who worked in the oil fields of Southern California in the 1930s and dreamed of returning to college at Caltech, this annual award recognizes undergraduate students for their contributions to the field of geology or geophysics.

Library Friends' Senior Thesis Prize
This prize was established by the Friends of the Caltech Libraries in 2010 to recognize senior theses that exemplify research and the effective use of library information resources. The thesis is an extensive, independent written work produced during the senior year, usually within a senior thesis course series. The University Librarian and the Friends of the Caltech Libraries oversee evaluation and make recommendations to the Undergraduate Academic Standards and Honors Committee for final selection. An oral presentation may be requested. At the discretion of the Friends of the Caltech Libraries, more than one award, or none, may be made in any year.

Mari Peterson Ligocki (B.S.'81) Memorial Fund
This award is made to one student who, through his or her personal character, has improved the quality of student life at Caltech. It recognizes the student who provides quiet support and kind encouragement to peers. This fund was established by Mr. José F. Helú Jr. (B.S. '79) to honor the memory of Mari Peterson Ligocki, who possessed these qualities. The award consists of dinner for two at the recipient's choice of a fine restaurant, and a grant toward any project or cause of the recipient's choosing. It may be seed money for a project in any field, whether science-related or not.

Mary A. Earl McKinney Prize in Literature
The Mary A. Earl McKinney Prize in Literature was established in 1946 by Samuel P. McKinney, M.D., of Los Angeles. Its purpose is to promote proficiency in writing. The terms under which it is given are decided each year by the literature faculty. It may be awarded for essays submitted in connection with regular literature classes, or awarded on the basis of a special essay contest.

Robert L. Noland Leadership Award
The Robert L. Noland Leadership Award is a cash award for upperclass students who exhibit qualities of outstanding leadership. The kind of leadership to be recognized is most often expressed in personal actions that have helped other people and that have inspired others to fulfill their leadership capabilities. The scholarship was set up by Ametek in 1978 in honor of its president, Robert L. Noland, a Caltech alumnus. Two or more awards are generally made each year.

Rodman W. Paul History Prize
The Rodman W. Paul History Prize was established in 1986 by some of his many colleagues and friends to honor Professor Paul's 35 years

of teaching and research at the Institute. The prize is awarded annually to a junior or senior who has shown unusual interest in and talent for history.

Doris S. Perpall SURF Speaking Prize
Robert C. Perpall (B.S. '52, M.S. '56) endowed this prize in memory of his late wife, Doris S. Perpall, to encourage students to prepare excellent SURF presentations. SURF Seminar Day is the first round of the Perpall Speaking Competition. The best presentations in each session are nominated for advancement to a second round, held in November. The final round is held in January. Three prizes are awarded annually.

Howard Reynolds Memorial Prize in Geology
The Howard Reynolds Memorial Prize in Geology is awarded to a sophomore or junior who demonstrates the potential to excel in the field of geology, and who actively contributes to the quality of student life at Caltech.

Herbert J. Ryser Scholarships
The Herbert J. Ryser Scholarships were established in 1986 in memory of H. J. Ryser, who was professor of mathematics at Caltech from 1967 to 1985. Professor Ryser contributed greatly to combinatorial mathematics and inspired many students with his carefully planned courses. The scholarships are given on the basis of merit, preferably in pure mathematics. Recipients are selected by the executive officer for mathematics after consulting the faculty.

San Pietro Travel Prize
This prize is awarded to one or more sophomores, juniors, or seniors to fund an adventurous and challenging summer experience that expands the recipient's cultural horizons and knowledge of the world.

Richard P. Schuster Memorial Prize
This Award is made from funds established by family, friends and colleagues of Richard P. Schuster, Jr., a graduate of Caltech and the Institute's Director of Development at the time of his death. The recipient is a junior or senior in Chemistry or Chemical Engineering; selection is based on financial need and a demonstration of academic promise.

Eleanor Searle Prize in Law, Politics, and Institutions
The Eleanor Searle Prize was established in 1999 by friends and colleagues to honor Eleanor Searle, who was the Edie and Lew Wasserman Professor of History at Caltech. The prize will be awarded annually to an undergraduate or graduate student whose work in history or the social sciences exemplifies Eleanor Searle's interests in the use of power, government, and law.

Renuka D. Sharma Prize and Award in Chemistry
This prize was established in 2009 by Professor Brahama D. Sharma, in memory of his daughter Renuka D. Sharma, to be given to a sophomore who has demonstrated outstanding performance in chemistry during his or her freshman year. The prize was donated to encourage scholastic achievement early in a student's career and is administered by the Division of Chemistry and Chemical Engineering.

Don Shepard Award
Relatives and friends of Don Shepard, class of 1950, have provided this award in his memory. The award is presented to a student, the basic costs of whose education have already been met but who would find it difficult, without additional help, to engage in extracurricular activities and in the cultural opportunities afforded by the community. The recipients—freshmen, sophomores, and juniors—are selected on the basis of their capacity to take advantage of and to profit from these opportunities, rather than on the basis of their scholastic standing.

Hallett Smith Prize
The Hallett Smith Prize was established in 1997 to commemorate Professor Smith's long career as one of this century's most distinguished Renaissance scholars. The cash prize is given annually by the literature faculty to the student who writes the finest essay on Shakespeare.

Paul Studenski Memorial Fund Prize
This travel grant is awarded to a Caltech undergraduate who would benefit from a period away from the academic community in order to obtain a better understanding of self and his or her plans for the future. The recipient is selected by the Caltech Y Studenski Committee.

Frank Teruggi Memorial Award
The Frank Teruggi Memorial Award was established in 1998 by friends and classmates of the late Frank Teruggi, a Caltech undergraduate who was murdered in Chile in 1973 during the military coup led by Augusto Pinochet. The annual award honors the spirit of Frank's life, especially "in the areas of Latin American studies, radical politics, creative radio programming, and other activities aimed at improving the living conditions of the less fortunate."

Morgan Ward Prize
The Morgan Ward Prize was established by the department of mathematics in 1963 to honor the memory of Professor Morgan Ward in recognition of his long service to mathematics and to the Institute. The competition is open only to freshmen and sophomores. An entry consists of a mathematical problem together with a solution or a significant contribution toward a solution. One or more winners are selected by a faculty committee acting on the advice of student judg-

es. Each prize is funded by the same source used to sponsor the Eric Temple Bell Prize.

Fredrick J. Zeigler Memorial Award
The Fredrick J. Zeigler Memorial Award was established in 1989 to honor Fredrick J. Zeigler, a member of the class of 1976 and an applied mathematics major. The award is given to a pure or applied mathematics student in his or her sophomore or junior year selected by the faculty in pure and applied mathematics. The award recognizes excellence in scholarship as demonstrated in class activities or in the preparation of an original paper or essay in any subject area.

Note: Prizes and awards may be subject to federal and state income tax.

GRADUATION REQUIREMENTS, ALL OPTIONS

To qualify for a Bachelor of Science degree at the Institute, students must obtain passing grades in each of the required courses listed below; must satisfy the additional requirements listed under the undergraduate options; must complete a minimum of 486 units (515 units for chemical engineering); and must achieve a grade-point average of not less than 1.9. Students must also register for the appropriate number of units that results in normal progress toward a B.S. degree.

Tuition for the baccalaureate degree is based on 12 terms of residence regardless of unit load each term or if a student completes graduation requirements a term(s) early. The 12-term tuition requirement is separate from and in addition to any other degree requirements. Students who are admitted as transfer students or 3/2 students may be granted advanced standing and tuition credit for academic work accepted in transfer to Caltech. However, transfer and 3/2 students must enroll for a minimum of six terms at Caltech. Any exceptions must be approved by the Dean of Undergraduate Students and the Vice President for Student Affairs.

Under normal circumstances the core and option requirements for the B.S. degree are those stated in the catalog published in the first year of a student's enrollment at Caltech. Faculty actions or decisions taken through the Faculty Board and the relevant faculty committees may occasionally result in changes to these requirements. In the event of exceptional circumstances, changes in an individual student's graduation requirements may be sought by petition to the relevant Faculty Representative(s) through procedures administered by the registrar. Questions should be addressed to the registrar.

Students must register for the Institute requirements in the year specified, unless they have previous credit. If for some reason they are not able to complete the requirements during the proper year, they must register at the earliest possible opportunity. (The Curriculum Committee may in unusual cases excuse undergraduate students from any of the following Institute or option requirements upon presentation of petitions.)

The Institute unit system is described in the opening paragraphs of section five of this catalog.

Core Institute Requirements, All Options

A Caltech education requires not just the depth of an option, but also considerable breadth in basic science, humanities, and social science. Caltech's core curriculum prepares students for the interdisciplinary nature of contemporary research in science and technology. This encourages a culture of problem solving, collaboration, and communication while providing valuable experience in all fields of science. Significant study in the humanities and social sciences is an important component of Caltech's core curriculum, giving alumni the ability to navigate the societal, political, and economic factors that influence, and are influenced by, their work.

The following requirements are applicable to incoming freshmen for 2015-16. Some information for continuing students has been provided as footnotes, but guidance on special cases must be sought. Courses used to satisfy core requirements may not be used to satisfy option electives.

Course	*Units*
1. Freshman Mathematics (Ma 1 abc)	27
2. Freshman Physics (Ph 1 abc)	27
3. Freshman Chemistry (Ch 1 ab)	15
4. Freshman Biology (Bi 1 or Bi 1 x)[1]	9
5. Menu Class (currently Ay 1, Ch/APh 2, ESE 1, EST 2, Ge 1, or IST 4)	9
6. Freshman Chemistry Laboratory (Ch 3 a)[2]	6
7. Additional Introductory Laboratory	6
8. Scientific Writing[3]	3
9. Humanities Courses (as defined below)	36
10. Social Sciences Courses (as defined below)	36
11. Additional Humanities and Social Sciences Courses	36
12. Physical Education	9

[1] Bi 8 or Bi 9 are acceptable alternatives to Bi 1 or Bi 1 x for students with a strong background in biology. Students who earned a 5 on the AP Biology exam may also petition the biology option representative to take a higher-level biology course of nine or more units, on grades , to fulfill the biology core requirement. Acceptable substitutions are : Bi/Ch 110, Bi 114, Bi 117, Bi 122, Bi 145a, Bi 145b and Bi/CNS/NB 150. Instructor permission, communicated to the option representative prior to registration is required. Note that this course cannot be used to fulfill another requirement.

[2] This requirement can also be met by completing Ch 3 x, Ch 4 a, Ch 8, or Ch/ChE 9.

[3] This requirement may be met either by taking a course approved by the student's option to satisfy this requirement, or by taking En/Wr 84.

Menu Classes

Menu classes are specifically designed for breadth. The intent of the menu class requirement is to introduce students to a subject that they did not plan to study. In many cases, it is the only class in that subject that they ever take; in other cases, they may decide to take more classes in that subject as a result. Students cannot take a menu class in a subject that they have already taken classes in or in their current option. This requirement must be completed by the end of sophomore year.

Introductory Laboratory Requirement
All students are required to take at least 12 units of laboratory work in experimental science during their freshman and sophomore years. Ch 3 a (6 units) or Ch 3 x (6 units) shall be taken during the freshman year. The additional 6 units must be chosen from one of the following: APh/EE 9 ab (6 units), APh 24 (6 units), Bi 10 (6 units), Ch 4 ab (9 units), Ch 8 (9 units), Ch/ChE 9 (9 units), EE/ME 7 (6 units), Ge 116 (6 units), Ph 3 (6 units), Ph 5 (9 units), Ph 8 bc (6 units), or a more advanced laboratory. Computational laboratory courses may not be used to satisfy this requirement.

Humanities and Social Sciences Requirements
All students must complete satisfactorily 108 units in the Division of the Humanities and Social Sciences. Of these, 36 must be in the humanities (art, English, film, history, history and philosophy of science, humanities, music, and philosophy) and 36 in the social sciences (anthropology, business economics and management, economics, law, political science, psychology, social science), in each case divided equally between introductory and advanced courses. The remaining 36 may be drawn from humanities and social sciences, including HSS tutorial courses and 9 units of either Wr 1 or Wr 2. They may not include BEM 102. They may not include reading courses unless credit has been granted by petition to the humanities or social science faculty. Language courses may count toward the additional 36 unit requirement, with the exception of beginning, intermediate, and advanced classes in the student's native language. In general, no more than 18 units of freshman humanities may be counted toward the 108-unit requirement.

Entering freshmen are required to take two terms of freshman humanities; that is, humanities courses numbered 20 or below in the *Catalog*. These classes introduce students to the basic issues in the three core disciplines of English, history, and philosophy. Successful completion of two terms of freshman humanities is a prerequisite for all humanities courses, except for foreign languages. It is *not* a prerequisite, however, for introductory social sciences. The freshman humanities classes may be taken in any two terms of the freshman year. Other humanities courses numbered 30 or greater are open only to students who have fulfilled the freshman humanities requirement.

To encourage breadth, students will have to take their two freshman humanities classes in different disciplines, the disciplines being English, history, and philosophy.

A student must take 18 units of advanced humanities courses as well. The classes that count as advanced humanities courses are those numbered 90 or above in art history, English, film, history, history and philosophy of science, humanities, music, and philosophy. Language courses do not count toward the advanced humanities requirement, except for courses that are cross-listed or taught concurrently with one of the listed subjects, such as film or humanities. Courses used to fulfill the advanced humanities requirement must be taken for grades. Courses taken on a pass/fail basis will not fulfill the requirement.

Since writing is an important method for developing and sharing ideas, all humanities courses, with the exception of some foreign languages and courses numbered between 29 and 90, require at least 4,000 words of composition. Instructors give extensive feedback on written work and help students improve their prose. As entering students may not be fully prepared for the writing in freshman humanities, all freshmen and transfer students take a writing assessment before the beginning of the fall term. On the basis of this assessment, some students may be required to pass WR 1, 2, 3, 4 and/or 50 before entering either freshman or advanced humanities classes.

Students are required to take two introductory social science courses and 18 units of related advanced undergraduate social science courses. Courses used to fulfill the advanced social science requirement must be taken for grades; courses taken on a pass/fail basis will not fulfill the requirement. The introductory social science courses must be drawn from the following list: either An 22 or An 23, Ec 11, Law 33, PS 12, either Psy 15, Psy 16, or Psy 20. The 18 units of advanced undergraduate social science courses (numbered 100 and above), in fields following at least one of their introductory courses, must be taken as indicated below:

Introductory Course	*Following Course*
An 22 or 23	advanced anthropology
Ec 11	advanced economics or BEM (except BEM 102)
Law 33	advanced law
PS 12	advanced political science
Psy 15, 16, or 20	advanced psychology

For instance, a student who has taken An 22 and Ec 11 may use 18 units of advanced anthropology courses, or 18 units of advanced economics, or 9 units of advanced anthropology and 9 units of advanced economics to fulfill the advanced social science requirement.

Included in the 12 humanities and social science courses, students must take at least 3 writing-intensive courses and these must be taken on grades. The graded advanced humanities courses count towards this total. A student can select another course from advanced humanities or a social science course with writing content (specifically Ec 105, Ec 129, Ec 130, Ec 140, PS 99 ab, PS 120, PS 141, or Law 136). These three writing-intensive courses should be spread out over the student's sophomore, junior, and senior years.

Physical Education Requirement

Before graduation, each undergraduate is required to successfully complete 9 units of physical education. This requirement may be satisfied entirely or in part by participation in intercollegiate athletics, or successful completion of physical education class course work. All grades are issued pass/fail. A maximum of 6 units per term may be applied toward graduation requirements, with the total not to exceed 36 units. Participation as a bona fide member of an intercollegiate team for the period covered by the sport in a given term satisfies the requirement for that term.

A broad program of instruction is provided each term. Late registration is permitted during the first week of each term, provided there is space available and with permission of the instructor. Standards for evaluation of student performance will be clearly defined at the beginning of each course.

Scientific Writing Requirement

The scientific writing requirement can be satisfied by taking an appropriate course offered by any division, or by taking En/Wr 84. The course used to satisfy this requirement must be taken on grades. All options also require a three-unit course in oral communication. Some options combine these two requirements into one course. At the discretion of the option, the scientific writing requirement can be satisfied by three units of additional work associated with a senior thesis, focused on effective written scientific communication.

Options	*Requirements*	
	Oral	*Written*
ACM, APh, CNS, CS, EE, EAS, ME	E 10	E 11
Ay	Ay 30	Ay 31
Bi, BE	Bi/BE 24	same
BEM, Ec, PS	En/Wr 84	same
ChE	ChE 126	Ch/ChE 91
Ch	Ch 90	Ch/ChE 91
En, H, HPS, Pl	En/Wr 84	same
GPS	Ge 109	En/Wr 94 or E 11
Ma	Ma 10	Ma 11
Ph	Ph 70	same

Typical First-Year Course Schedule, All Options

Differentiation into the various options begins in the second year.

		Units per term				
		1st		2nd		3rd
Ma 1 abc	Freshman Mathematics	9		9		9
Ph 1 abc	Freshman Physics	9		9		9
Ch 1 ab	General Chemistry	6		9		0
Bi 1	Principles of Biology	0		0		9
Ch 3 a	Fundamental Techniques of Experimenal Chemistry[1]	6	or	6	or	6
	Introductory courses in the humanities and social sciences. A wide choice of alternatives will be available to students; the registrar will announce the offerings for each term.	9		9		9
	Introductory laboratory courses[2]	x		x		x
	Menu course[3] or additional electives	x		x		x
PE	Physical education[4]	3		3		3

x—Except for the minimum laboratory unit requirement, the number of units chosen here is optional. If a student chooses no electives except physical education and takes the minimum permissible laboratory courses, the total unit requirement will usually be in the range of 39 to 45. First- and second-term freshmen will be limited to 45 units of classroom and laboratory courses. A total load—including electives—of more than 48 units per term is considered a heavy load. Loads of more than 51 units for freshmen or 54 units for upperclass students require approval by the dean of students.

[1] *This course is offered in each of the three terms. Students may also take Ch 3 x.*

[2] *The additional 6 units must be chosen from one of the following: APh/EE 9 ab (6 units), APh 24 (6 units), Bi 10 (6 units), Ch 4 ab (9 units), Ch 8 (9 units), Ch/ChE 9 (9 units), EE/ME 7 (6 units), Ge 116 (6 units), Ph 3 (6 units), Ph 5 (9 units), Ph 8 bc (6 units) or a more advanced laboratory course.*

[3] *Students must take a menu course in their freshman or sophomore year. These courses are offered third quarter only. It is also possible to take one of these courses as an elective. Menu courses currently include Ay 1, Ch/APh 2, ESE 1, EST 2, Ge 1, or IST 4.*

[4] *Three terms (9 units) of PE are required for the B.S. degree. Students need not elect to take the required PE in the freshman year. It may be taken in any three terms before graduation.*

Other First-Year Courses

In addition to the required core classes described on the previous pages, freshmen are encouraged to participate in freshman seminar classes, frontier classes, research tutorials and other research opportunities.

Starting in the 2011–12 academic year, Caltech began offering a series of freshman seminars in which 10 to 15 freshmen and a faculty member explore in depth an exciting topic in the lab, around a table, or in the field. These courses, described on page 528, cover a wide range of topics, including earthquakes, gravitational waves, and the science of music. Instructors may allow upperclassmen to enroll in these seminars after the conclusion of the pre-registration period for the upcoming term.

Caltech also offers a series of "frontier courses" that involve a weekly presentation by a faculty member on a topic of current research. These courses often meet at lunch time and serve pizza; hence, students refer to the courses as "pizza courses." The frontier courses are an opportunity for students to meet the Caltech faculty and to hear about state-of-the-art research projects for the summer or academic year. There are a total of 10 frontier courses offered for freshmen in biology, chemistry, mathematics, physics, geology and planetary sciences, engineering, computer science, chemical engineering, bioengineering, and electrical engineering.

Currently there are three "research tutorials" for freshmen: one in physics, one in biology, and one in chemistry. These tutorials have many of the same features as the freshman seminars. In physics, the research tutorial includes approximately seven freshmen and extends over three academic terms plus the summer. The purpose is to demonstrate how research opportunities arise, are evaluated, and are tested, and how the ideas that survive develop in larger projects. In biology and chemistry, the tutorials are offered in the winter and spring quarters and involve small group discussions on special areas or problems in biology, biotechnology, and chemistry.

More than 80 percent of Caltech students participate in research at some point in their academic career. Students may embark on research activities by registering for research credits with a faculty member, by working in a laboratory for pay during the summer or academic year, by completing a senior thesis, or by participating in Caltech's Summer Undergraduate Research Fellowship (SURF) program. The SURF program is described on page 30.

Aerospace Minor

The aerospace minor is intended to supplement one of Caltech's undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major or who may wish to pursue a graduate program involving aerospace or aeronautical engineering. Students completing the aerospace minor requirements will have the phrase "minor in aerospace engineering" added to their transcripts.

Ae Minor Requirements

1. Complete Ae 105 abc.
2. Complete a second three-term 100-level Ae class, chosen from Ae 101 abc, 102 abc, 104 abc, 121 abc, Ae/Ge/ME 160 ab, or 27 units of selected Ae courses approved by the minor adviser. All Ae courses to be applied to fulfill the aerospace minor requirements must be taken for grades, and students must maintain an average grade of B or higher for all courses with no individual grade lower than a C. Courses that are used

to satisfy the aerospace minor cannot be used to satisfy course requirements in the major options. Courses taken as part of the aerospace minor are counted toward the total 486-unit Institute graduation requirements. A typical course sequence would be to take Ae 105 abc and the second Ae course in the senior year.

Applied and Computational Mathematics Option

The undergraduate option in applied and computational mathematics within the Computing & Mathematical Sciences department seeks to address the interests of those students who want to combine their basic studies in mathematics with considerable involvement in applications. This program is designed to give students a thorough training in fundamental computational and applied mathematics and to develop their research ability in a specific application field. The fields of application include a wide range of areas such as fluid mechanics, materials science, and mathematical biology, engineering applications, image processing, and mathematical finance. The training essential for future careers in applied mathematics in academia, national laboratories, or in industry is provided, especially when combined with graduate work, by successful completion of the requirements for an undergraduate degree in applied and computational mathematics. Complete programs will be worked out with faculty advisers.

Double Majors

Students interested in simultaneously pursuing a degree in a second option must fulfill all the requirements of the ACM option. Courses may be used to simultaneously fulfill requirements in both options. To enroll in the program, the student should meet and discuss his/her plans with the option representative. In general, approval is contingent on good academic performance by the student and demonstrated ability for handling the heavier course load.

Option Requirements

1. The ACM Option requires the analytical tracks of Ma 1 b and Ma 1 c.
2. Ma 2, Ma 3, Ma 6 abc, Ph 2 abc, ACM 11, CS 1, E 10, ACM 95 ab, Ma 108 abc, CMS/ACM 104, ACM 101 ab, ACM 106 ab, CMS/ACM/EE 116, ACM 216 and CMS/ACM 113.
3. One 27-unit 100-or-higher-level course in science or engineering approved by the option representative.
4. Passing grades must be obtained in a total of 486 units, including the courses listed above. Courses satisfying option requirements must be taken for grades (except when courses are only available P/F) and passed with a grad of C- or higher.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2	Differential Equations	9	-	-
Ma 3	Introduction to Probability and Statistics	-	9	-
Ma 6 abc	Introduction to Discrete Mathematics	9	9	9
Ph 2 abc	Sophomore Physics	9	9	9
ACM 11	Intro. to Matlab and Mathematica	-	-	6
CS 1	Intro. to Computer Programming	9	-	-
	HSS electives	-	9	9
	Electives	9	12	12
		45	48	45
Third Year		*1st*	*2nd*	*3rd*
Ma 108 abc	Classical Analysis	9	9	9
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
ACM/ CMS104	Linear Alegebra & Appl. Operator Theory	12	-	-
	HSS electives	9	9	9
	Electives[1]	-	12	12
		30	42	42
Fourth Year		*1st*	*2nd*	*3rd*
ACM 101 ab	Methods of Applied Mathematics	12	12	-
ACM 106 ab	Intro. Methods of Comput. Math	-	12	12
CMS/ACM/ CMS 116	Intro. to Stoch. Proc. and Modeling	9	-	-
ACM 216	Markov Chains, Discrete Stoch. Proc. and Appl.	-	9	-
CMS/ ACM 113	Mathematical Optimization	9	-	-
	HSS electives	9	-	-
	Electives[1]	9	9	30
		48	42	42

[1] *See items 2, 3, and 4 under option requirements.*

Applied Physics Option

The applied physics option is designed to extend knowledge of the principles of pure physics to the development of new technologies. Research in applied physics focuses primarily on problems of technological importance. The interdisciplinary nature of this option allows considerable flexibility in course work, training and individual research interests to enhance maximum breadth and depth.

Current areas of specialization within Applied Physics span a wide range of topics such as Photonics including multiwavelength fiber telecommunications, integrated microphotonic and nanophotonic devices, holographic data processing and storage, and optical approaches to quantum computation; Solid-state materials and device work including nanostructured materials and devices, wide bandgap semiconductors and heterostructures for optoelectronics, photovoltaics, novel memory devices, and spin-dependent transport; Biophysics including single-molecule-scale studies of the mechanics of DNA, proteins, and their assemblies; Plasma-physics including spheromak plasmas for fusion application, plasma processes occurring in the sun, and the dynamics of pure electron plasmas; Hydrodynamics, nonlinear dynamics and thermal behavior in small scale systems including symmetry breaking in soft condensed matter, micro/nanofluidic, optofluidic, and biofluidic devices, optical trapping in fluids, pattern formation and phase separation in nanoscale films and convection-diffusive phenomena in natural and mimetic systems.

Option Requirements

1. E 10 and E 11. E 11 can be satisfied by three units of additional work associated with the senior thesis (APh 78 or 79), or by taking Ph70, En 84 or Bi24.
2. Any three of the following: APh/EE 9 b, APh 24, Ph 3, Ph 5, Ph 6, or Ph 7.
3. Ph 12 abc, APh 17 ab or APh 105 ab, Ph 106 abc, and Ph 125 ab or Ch 125 ab.
4. Ma 2, Ma 3, and ACM 95 ab.
5. Either APh 78 abc, or one term of APh 77 and one term of any of the following: APh 77, Ph 77, EE 91, Ch 6, Ae/APh 104 bc, and MS 90. Any substitutions or additions require prior approval of the option representative.
6. One additional advanced sequence of APh courses numbered over 100, such as: APh 101 abc, APh/MS 105 abc, 114 abc, APh/Ph 115 and APh/Ph/Ae 116, APh/EE 130, 131, and 132, APh 156 abc, or BE/APh 161 and 162. Note that APh 100 and APh 200 do not satisfy this requirement. Any substitutions or additions require prior approval of the option representative.
7. Passing grades must be earned in a total of 486 units, including the courses listed above. No course in fulfillment of option requirements may be taken on a pass/fail basis.
8. Any student whose grade-point average is less than 1.9 at the end of the academic year in the subjects listed above may be refused permission to continue work in this option.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 12 abc	Sophomore Physics	9	9	9
Ma 2 and 3	Sophomore Mathematics	9	9	0
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	HSS electives	9	9	9

	Laboratory electives[1]	6	6	6
	Other elective	9	0	9
		42	45	45
Third Year				
Ph 125 ab	Quantum Mechanics	9	9	0
APh 110 ab	Topics in Applied Physics	2	2	0
APh 17 ab	Thermodynamics and Stat. Mech	9	9	0
Ph 106 abc	Topics in Classical Physics	9	9	9
	HSS electives	9	9	9
	Other electives[2]	9	9	27
		47	47	45
Fourth Year				
APh 78 abc	Senior Thesis, Experimental[3]	9	9	9
or				
APh 77	Laboratory in Applied Physics[3]	-	9	9
	Advanced Elective[2]	9	9	9
	HSS electives	9	9	9
	Other electives including APh100	27	18	18
		45	45	45

[1] *See item 2, option requirements.*
[2] *See item 6, option requirements.*
[3] *See item 5, option requirements.*

Suggested Electives

Students are encouraged to obtain a well-rounded course of study pursuant to the B.S. degree in applied physics. The option representative and/or undergraduate adviser will gladly assist students in choosing appropriate elective courses. Students ultimately interested in pursuing an advanced degree in applied physics or related fields are encouraged to complete a senior thesis project through APh 78 or 79.

Astrophysics Option

With the goal of understanding the physical processes that govern the universe, its constituents, and their origins and evolution, astronomy uses the apparatus and methodology of physics to gather and interpret data. Theoretical work and technology development round out astrophysics. In what follows, we use the terms "astronomy" and "astrophysics" interchangeably.

The astrophysics option is designed to give the student an understanding of the basic facts and concepts of astronomy today, to stimulate his or her interest in research, and to provide a basis for graduate work in astronomy/astrophysics. The sequence Ay 20, 21 constitutes a solid introduction to modern astrophysics and may be taken either sophomore or junior year, with more advanced courses (Ay 101, 102, plus Ay electives) taken in the junior and senior years. It is desirable for a student to gain as broad a background as possible in related fields of science and engineering.

Attention is called to the fact that any student whose grade-point average is less than 1.9 at the end of an academic year in the subjects listed in the Division of Physics, Mathematics and Astronomy may, at the discretion of his or her department, be refused permission to continue the work in this option.

Option Requirements

1. Ay 20, 21, 101, 102, 30, 31, and one term of Ay 141, Ma 2, Ma 3, Ph 2 abc or Ph 12 abc, Ph 125 ab, and Ph 106 abc.
2. Any three of Ph 3, Ph 5, Ph 6, Ph 7, or Ay 105. APh 23 and 24 taken as a pair may be substituted for one of these labs.
3. 63 additional units of Ay or Ph courses.
4. 27 additional units of science or engineering electives, of which 18 must be outside the Division of Physics, Mathematics and Astronomy. Core classes (see pages 216-220) or other introductory-level courses such as CS 1 do not count toward fulfillment of this requirement.
5. Passing grades must be earned in a total of 486 units, including the courses listed above. Courses satisfying requirements 1, 2, and 3 must be taken for grades unless they are pass/fail only.

Typical Course Schedule

		Units per term 1st	2nd	3rd
Second Year				
Ph 12 abc or Ph 2 abc	Sophomore Physics	9	9	9
Ma 2, Ma 3	Sophomore Mathematics	9	9	-
Ay 20	Basic Astronomy and the Galaxy	10	-	-
Ay 21	Galaxies and Cosmology	-	9	-
Ay 30	Intro. to Modern Research	-	3	-
	Physics Laboratory	-	-	9
ACM 95 ab	Intro. Methods of App. Math.		12	12
	HSS electives	9	9	9
		37	51	39
Third Year				
Ph 125 abc	Quantum Mechanics	9	9	9
Ph 106 abc	Topics in Classical Physics	9	9	9
Ay 101	The Physics of Stars	-	11	-
Ay 102	Physics of the Interstellar Medium	-	-	9
Ay 104	High Energy Astrophysics			9
Ph 127a	Statistical Physics	9	-	-
	HSS electives	9	9	9
	Astronomy, physics, or APh electives	-	9	-
		36	47	45

Fourth Year

Ay 31	Written Communication	-	-	3
Ay 105	Astronomy Instrumentation Lab	-	10	-
	Astronomy, physics, or APh electives	9	9	-
Ay 78	Senior Thesis	9	9	9
	HSS electives	9	9	9
Ay 141c	Research Conference in Astronomy			3
	Electives	18	9	18
		45	46	42

An ability to present one's work is vital to a successful career in research and teaching. The oral communications requirement is satisfied by presenting during a term of Ay 141. Ay 31 satisfies the written communication requirement. Students are encouraged (but not required) to undertake research leading to a senior thesis; credit for this work is provided through Ay 78. Non-thesis research credits may be earned through Ay 142 with a maximum of 9 units per term. Computational skills may be acquired through Ph 20–21, Ay 117, Ay 190, ACM 106, or equivalent classes. Students are strongly advised to take advanced mathematical methods in ACM95 and Ph 129, and an advanced statistical physics or thermodynamics course such as Ph 127.

Suggested Electives

The student may elect any course offered in any division in a given term, provided that he or she has the necessary prerequisites for that course. The following courses are useful to work in various fields of astronomy and astrophysics: ACM 95, ACM 106, APh 23/24, Ay 104, Ay 105, Ay 117, Ay 121–127, Ay 190, Ch 125, EE 45, EE/Ae 157, Ge/Ay 11 c, Ge 103, Ge/Ch 128, Ge 131, Ge/Ay 132, 133, 137, Ma 4, Ma 112, ME 11, ME 12, Ph 20–22, Ph 77, 101, 127, 129, 136, 199, 236 (this is not necessarily a complete list).

Bioengineering Option

Aims and Scope

The undergraduate bioengineering option provides a foundation for graduate studies and career paths that require the application of engineering principles to the design, analysis, construction, and manipulation of biological systems, and in the discovery and application of new engineering principles inspired by the properties of biological systems. By graduation, students are expected to have learned basic laboratory and engineering methods used in a broad range of bioengineering sub-disciplines.

Students will also have learned quantitative and analytic skills vital to experiments and system designs. Graduating students are expected to be able to critically evaluate and understand bioengineering literature, and be able to work in a team and communicate effectively.

To accomplish these goals, students are expected to complete a series of required courses designed to introduce them to a representative range of bioengineering sub-disciplines, provide them with a solid quantitative analysis foundation, provide them with opportunities to work in teams through a number of project oriented courses. Students will receive instruction in scientific communications through Bi/BE24.

Undergraduate research is encouraged both during the academic year and through participation in summer research programs.

Students should present a plan for satisfying all degree requirements to their academic advisor by the end of the third term of the second year.

Students with a grade-point average lower than 1.9 will not be allowed to continue in the option except with special permission from the option representative.

Option Requirements

1. BE 1; either BE 150 or BE 159; BE/APh 161; ChE/BE 163; BE/CS/CNS/Bi 191 a.
2. Experimental methods: Bi 1 x; BE/EE/MedE 189 a; ChE 130.
3. Biology, chemistry and physics: two terms out of three from Ph 2 abc; Bi 8; Bi 9; Ch 25; Ch 41 a; Bi/Ch 110. One advanced biology course selected from Bi/Ch 111, Bi/Ch 113, Bi 114, Bi 117, Bi 122, Bi 145 ab, Bi/CNS/NB 150, BE 150. Students may pass out of Bi 8 and Bi 9 via placement exams administered by the Biology Option.
4. Mathematical and computational methods: ACM 95 ab; CDS 110 or ChE 105; Ma 2, Ma 3; 9 units selected from CS 1, CS 2, CS 3.
5. 36 units of BE electives (selected from the elective lists below or approved by the student's academic adviser).
6. Communication: Bi/BE 24.
7. Courses satisfying option requirements must be taken for grades (except when courses are only available P/F). Passing grades must be earned in a total of 486 units.

BE Electives

BE 98 (for a maximum of 12 units), BE/Bi 101, BE/Bi 103, BE 150, BE 153, BE 159, BE/EE/MedE 189 b, BE/CS/CNS/Bi 191 b, Ae/BE 242, Bi/Ge 105, Bi/CNS/NB 162, Bi/BE 177, Bi/Ge 180, Bi/BE 227, EE/BE/MedE 166, EE/BE/MedE 185, MedE/BE/Ae 243, Ph/APh/EE/BE 118 abc

Other Relevant BE-Approved Electives

Biodevices: EE 112, EE 113, EE/MedE 114 ab, APh/EE 9 ab, EE 45, EE 111, EE 151, Ph/APh/EE/BE 118 abc

Biomechanics: ME 19 ab, ME 12 abc, ME 14, Ae/APh/CE/ME 101 abc, Ae/APh/CE/ME 102 abc, Ae/APh 104 abc

Synthetic biology: CS 21, Ch 24, Ch 41 bc, ChE/Ch 148, ChE/Ch 164, ChE/Ch 165

Typical Course Schedule

		Units per term		
		1st	2nd	3rd
First Year				
Ma 1 abc	Freshman Mathematics	9	9	9
Ph 1 abc	Freshman Physics	9	9	9
Ch 1 ab	General Chemistry	6	9	-
Ch 3 a	Fundamental Techniques of Experimental Chemistry	6	-	-
Bi 1 x	The Great Ideas of Biology: An Introduction Through Experimentation	-	-	9
BE 1	Frontiers in Bioengineering	-	1	-
	Introductory HSS courses	9	9	9
	Physical education	-	-	3
		30	37	39

		Units per term		
		1st	2nd	3rd
Second Year				
Ma 2, Ma 3	Sophomore Mathematics	9	9	
-				
Ph 2 ac	Sophomore Physics	9	-	9
Ch 41 a	Organic Chemistry	9	-	-
Ch 25	Introduction to Biophysical Chemistry	-	-	9
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
	Menu course	-	-	9
	General and BE electives	x	x	x
	HSS electives	x	x	x
	Physical education	x	x	x
		42–45	42–45	42–45

		Units per term		
		1st	2nd	3rd
Third Year				
ACM 95 ab	Introductory Methods of Applied Mathematics	-	12	12
BE/EE/ MedE 189 a	Design and Construction of Biodevices	12	12	-
Bi/Ch 110	Introduction to Biochemistry	12	-	-
ChE/BE 163	Introduction to Biomolecular Engineering	9	-	-
	Computational methods requirement	x	x	x
	General and BE electives	x	x	x

		1st	2nd	3rd
Bi/BE 24	Technical Communication for Biological Scientists and Engineers	6	-	-
	HSS electives	x	x	x
	Physical education	x	x	x
ChE 130	Biomolecular Engineering Laboratory	-	-	9
		42–45	42–45	42–45

		Units per term		
		1st	*2nd*	*3rd*
Fourth Year				
CDS 110 *or* ChE 105	Introductory Control Theory *or* Dynamics and Control of Chemical Systems	x	-	x
BE/APh 161	Physical Biology of the Cell	-	12	-
BE/CS/CNS/Bi 191 a	Biomolecular Computation	-	9	-
BE 150	Design Principles of Genetic Circuits	-	-	9
or BE 159	Signal Transduction and Biomechanics in Eukaryotic Cell Morphogenesis	-	9	-
	General and BE Electives	x	x	x
	Advanced biology and biology lab requirements	x	x	x
	HSS electives	x	x	x
	Physical education	x	x	x
		42–45	42–45	42–45

Biology Option

The undergraduate option in biology is designed to build on a solid foundation in mathematics and physical science by providing an introduction to the basic facts, concepts, problems, and methodologies of biological science. The option serves as a basis for graduate study in any field of biology or for admission to the study of medicine. Instruction is offered in the form of participation in the ongoing research programs of the division, as well as in formal course work. Course work emphasizes the more general and fundamental properties of living organisms, and areas of current research interest, rather than the traditional distinct fields within the life sciences.

The division encourages undergraduate participation in its research program and believes that research participation should be a part of each student's program of study. Students may elect to prepare an undergraduate thesis (Bi 90). Research opportunities may be arranged with individual faculty members, or guidance may

be obtained from a student's individual faculty adviser in the division or from the biology undergraduate student adviser.

The requirements listed below for the biology option are minimal requirements. An adequate preparation for graduate work in biology will normally include additional elective research or course work in biology and/or advanced course work in other sciences or in mathematics. Flexibility to accommodate varied individual scientific interests, within the broad scope of biology, is achieved through the provision of elective courses, arrangements for individual research (Bi 22), and tutorial instruction (Bi 23). In addition, arrangements may be made to take courses at neighboring institutions in fields of biology that are not represented in our curriculum.

Premedical Program
The undergraduate course for premedical students is essentially the same as that for biology students and is intended as a basis for later careers in research as well as in the practice of medicine. It differs in some respects from premedical curricula of other schools; however, it has been quite generally accepted as satisfying admission requirements of medical schools.

It is recommended that all students contemplating application to medical school consult with the premed adviser at the Career Development Center or Professor David Chan in the Division of Biology and Biological Engineering.

Option Requirements

The following required courses must all be taken on grades, with the exception of Bi 8 if taken in freshman year and Bi 22. Freshmen taking Bi 8 must maintain shadow grades that indicate satisfactory progress.

1. Bi 8, Bi 9, Bi 117, Bi 122, Bi/CNS/NB 150, and Ch 41 abc.
2. Ma 2, Ma 3, and any two terms of Ph 2 abc. These courses need not be taken consecutively or in a fixed order. This requirement can also be satisfied in part by successfully taking a "reasonable" replacement for any of these required courses. A "reasonable" replacement will be defined by: (1) Equally or more advanced quantitative coursework; and (2) Essentially similar scope of subject matter as the course replaced. The Biology option representative will be empowered to make this determination with aid of an advisory list which can be updated as relevant new courses are developed inside and outside of biology.
3. One advanced laboratory course (100- or 200-level), or at least 12 units of independent research (Bi 22).
4. Two courses chosen from Bi/Ch 110, 111, 113, and/or Bi/Ch 132.
5. Scientific writing requirement met by taking Bi/BE 24 (six units), or by taking any other writing course such as E 11, En 84 or Ge 13 (three units) plus oral presentation at SURF Seminar Day or equivalent, with option representative approval.
6. A total of 170 units of biology must be taken and passed (Bi 1, Bi 2, and Bi 10 cannot be counted toward this total). Units within this total which are not accounted for by the requirements above are biology electives.

Biology electives must include at least 8 biology classes which satisfy the following:

a. At least four elective courses must be taken for letter grades.
b. Elective courses taken for letter grades should span at least two of the "tracks" indicated below.
c. At least two graded elective courses (from different tracks must be for at least nine units.

d. Substantial lab research for credit (Bi 22) beyond the 12-unit minimum can be counted among the electives.

7. Passing grades must be earned in a total of 486 units, including the courses listed above.

Biology Tracks

These groups of courses are logically related, and several courses within one track should be taken to build depth. Electives must also include different courses from at least two different tracks to build breadth. Non-elective courses included in the general option requirements that provide logical background for particular tracks are indicated in parentheses.

a. Biochemistry and molecular biology: (Bi 8, Bi 9) BE/Bi 101, BE/Bi 103, Bi/Ch 110, 111, 113, 132 (if not taken to satisfy item 3; no double-counting); Bi 129; Bi/NB/BE 155; BMB/Bi/Ch 170, 173, 174; Bi 181, 189, 206; Ch/Bi 231. Note: Ch 24 and Ch 7 or Ch 145 are also recommended for students interested in this track.
b. Genetics: (Bi 8, Bi 117, Bi 122) Bi 115, 129, 181, 188, 190, 206; Bi/CNS/NB 150, 220; Bi/CNS/BE/NB 230.
c. Microbiology: Bi 115, , ESE/Bi 166, 168; Ge/ ESE 170.
d. Developmental biology and evolution: (Bi 117, Bi 122) Bi/ Ge105; Bi 118; Bi/CNS/NB 157; Bi/CNS 158;; Bi 188, 190, 204, 214; Bi/BE 177, 182, 227.
e. Neurobiology: (Bi/CNS/NB 150) Bi/CNS 162, 164; Bi/CNS/ NB 153, 157, 184, 185, 195, 216, 217, 220; Bi/NB 202; Bi/NB/ BE 155; Bi/CNS/BE/NB 230; CNS/Bi/SS/Psy/NB 176; CNS/ Bi/EE/CS/NB 186; CNS/Bi/NB 247.

   Behavior/psychology subcluster: CNS/SS/ Psy/Bi 102 ab, CNS/ Psy/Bi 131, Bi/CNS/NB 216, 217, 220; CNS/Bi/SS/Psy/NB 176; CNS/Bi/NB 256.
f. Computational and systems biology: BE/Bi 101, 103, 203; (BE 150), Bi/CNS/NB 153, Bi 181; Bi/BE 182; Bi/CNS/NB 185, Bi 192, Bi 199, Bi/CNS/NB 184, 195, 220; CNS/Bi/EE/CS/NB 186; CNS/Bi/Ph/CS/NB 187; BE/CS/CNS/Bi 191ab; CNS/ Bi/NB 247; 256. CS programming courses are highly recommended for those interested in this track.
g. Organismal biology: Bi 114, 115, 118, 129, 145 ab, 188, 204, 214; Bi/CNS/NB157; Bi/CNS 158; Bi/NB 202.
h. Cell biology: (Bi 9) Bi/Ch 113 if not taken to satisfy requirement item 3, Bi 115, 118, 129, 145 ab, 189.

Planning the Biology Course Schedule

• Most students interested in biology elect to take Bi8 and Bi9 in their first year, to open access to the widest range of biology electives.

• Students may place out of the option requirement to take Bi 8 or Bi 9 by passing an exam and then earning a passing grade in Bi/Ch 111 or Bi/Ch 113, respectively, instead. The exam for placing out of Bi 8 and Bi 9 is given late in the fall term of freshman year, and is open to students who have an unusually strong background in biology, e.g., substantial research experience. Some students who score a 5 on the advanced placement exam in biology may also qualify to take the exam.

The placement exam is given by direct arrangement between the interested students and the faculty teaching Bi8 and/or Bi9.

• Bi 10 is not required for the biology option but is commonly taken by biology students to meet the Institute introductory laboratory requirement.

• Prerequisites listed for individual biology courses are advisory, not compulsory. They indicate the kind of background that is assumed for the work level of the course. In general they may be waived with the instructor's permission.

• Ch 24 and Ch 25 are strongly recommended for students interested in postgraduate work in biology, as physical chemistry is required by most graduate programs.

• Additional courses of potential interest to biology majors include Ge 11 b, BE/APh 161, BE 163, and advanced geobiology courses.

• Undergraduates are generally welcome to take 200-level courses with the instructor's permission or strong preparation, unless otherwise indicated.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
First Year				
Ma 1 abc	Freshman Mathematics	9	9	9
Ph 1 abc	Freshman Physics	9	9	9
Ch 1 ab	General Chemistry	6	9	-
Ch 3 a	Chemistry Lab	-	6	-
	Freshman Humanities	9	-	9
CS 1	Intro to Computer Programming	9	-	-
Bi 8	Intro to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Intro to Biology Laboratory	-	-	6
		42	42	42

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2	Differential Equations	9	-	-
Ma 3	Intro to Probability and Statistics	-	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ch 41 abc	Organic Chemistry	9	9	9
	Introductory Social Sciences	9	9	-
	Advanced Humanities	-	-	9
Bi 122	Genetics	9	-	-
Bi 117	Developmental Biology	-	9	-
Bi 190	Systems Genetics	-	-	6
Bi 188	Human Genetics and Genomics	-	-	6
Bi 22	Undergraduate Research	-	-	12+
		45	45	42+
Third Year				
	Advanced Humanities	9	-	-
	Advanced Social Sciences	9	-	9
	Additional HSS	-	-	9
Bi 150	Introduction to Neuroscience	10	-	-

Bi/Ch 110	Introduction to Biochemistry	12	-	-
Bi/Be 24	Technical Communication	6	-	-
Bi 199	Intro to MATLAB for Biologists	-	6	-
Bi/Ch 111	Biochemistry of Gene Expression	-	12	-
Bi 182	Gene Regulation Systems	-	6	-
Bi 129	Biology of Cancer	-	9	-
Bi/CNS/NB 164	Tools of Neurobiology	-	9	-
Bi 115	Viruses and their Hosts	-	-	9
Bi 158	Vertebrate Evolution	-	-	9
Bi/CNS/NB 220	Genetic Dissection of Neural Circuit Function	-	-	6
		46	42	42
Fourth Year				
	Addition HSS	9	9	9
Bi 145 ab	Tissue and Organ Physiology	9	9	-
Bi 118	Developmental Systems	6	-	-
Bi 90	Undergraduate Thesis	12+	12+	12+
Bi 192	Intro to Systems Biology	6	-	-
Bi 114	Immunology	-	9	-
Bi/B1 101	Order of Magnitude Biology	-	6	-
Bi 189	The Cell Cycle	-	-	6
Bi 113	Biochemistry of the Cell	-	-	12
Bi 214	Hematopoietic System	-	-	6
		42+	45+	45+

Business, Economics, and Management Option

The business, economics, and management (BEM) option provides students with the analytical tools to operate successfully in a modern volatile business environment. The emphasis is on entrepreneurship, finance and strategy, in a free market competitive or strategic situation. Today's business environment is complex and required courses in this option are therefore highly analytical.

Option Requirements

It is highly recommended to take a statistics/econometrics course, as well as BEM 102 and BEM 103 before other BEM courses.

1. Ec 11, Ec 122, MA 3, PS/Ec 172.
2. BEM 102, BEM 103, BEM 104, BEM 105, BEM 106 and BEM 110.
3. Writing/oral presentation courses: a scientific writing requirement course, and a three-unit course in oral communication, offered by any division (some options combine these two requirements into one course, that can be taken to satisfy this requirement), or En/Wr 84. The course used to satisfy this requirement must be taken on grades.
4. Five courses, to be chosen from the menu (may be taken pass/fail): any BEM courses (excluding the ones listed under 1 and 2 above), Ec 105, 106, 116, 121 ab, 122, 123, 129, 130, 131, 132, 135, 145, Ec/PS 160 abc, PS 12, Psy 15, Psy 20, ACM 113, ACM/EE/CMS 116, AN/PS 127, Ge/ESE 118, Ma 112a, Ma/ACM

144 ab, Law 134, 135. Other courses with permission of BEM option representative.

5. 45 additional units of science (including anthropology, economics, political science, psychology, social science), mathematics, and engineering courses; this requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by any course with a number less than 10 (may be taken pass/fail).
6. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 & Ma 3	Sophomore Mathematics	9	9	-
	Menu Course	-	-	9
Ec 11	Introduction to Economics	9	-	-
BEM 102	Introduction to Accounting	9	-	-
BEM/EC 131	Market Design	9	-	-
PS/Ec 172	Game Theory	-	-	9
	Electives[1]	9	36	27
		45	45	45
Third Year				
BEM 103	Introduction to Finance	9	-	-
BEM 104	Investments	-	9	-
BEM 106	Competitive Strategy	-	9	-
EC 122	Econometrics	9	-	-
	Electives[1]	27	27	45
		45	45	45
Fourth Year				
En/Wr 84 (or 3 unit course in oral communication and a scientific writing requirement course		-	-	9
BEM 105	Options	9	-	-
BEM 110	Venture Capital	-	9	-
	Electives[1]	36	36	36
		45	45	45

[1] *See option requirements 4 and 5.*

Chemical Engineering Option

The chemical engineering option is designed to prepare its students for either graduate study or research and development work in industry. This is accomplished by providing broad and rigorous training in the fundamentals of chemical engineering while maintaining a balance between classroom lectures and laboratory experience. The program also strives to develop in each student self-reliance, creativity, professional ethics, an appreciation of the societal impact of chemical engineering, and an understanding of the importance of continuing intellectual growth.

Chemical engineering involves applications of chemistry, physics, mathematics, and, increasingly, biology and biochemistry. In addition to these disciplines, the chemical engineering curriculum includes the study of applied and computational mathematics, fluid mechanics, heat and mass transfer, thermodynamics, chemical kinetics and chemical reactor design, and process control. Because of this broad-based foundation that emphasizes basic and engineering sciences, chemical engineering is perhaps the broadest of the engineering disciplines.

Because many industries utilize some chemical or physical transformation of matter, the chemical engineer is much in demand. He or she may work in the manufacture of inorganic products (ceramics, semiconductors, and other electronic materials); in the manufacture of organic products (polymer fibers, films, coatings, pharmaceuticals, hydrocarbon fuels, and petrochemicals); in other process industries; or in the biotechnology, pharmaceutical, or biomedical industries. Chemical engineering underlies most of the energy field, including the efficient production and utilization of coal, petroleum, natural gas, and newer technologies such as biofuels, fuel cells, and solar energy conversion technologies. Air and water pollution control and abatement and the study of climate change, its impacts, and its mitigation are also within the domain of expertise of chemical engineers. The chemical engineer may also enter the field of biochemical engineering, where applications range from the utilization of microorganisms and cultured cells, to enzyme engineering and other areas of emerging biotechnology, to the manufacture of foods, to the design of artificial human organs.

Key educational objectives of our chemical engineering curriculum are to prepare students for professional practice at the forefront of chemical engineering or for graduate school, and to become leaders in engineering, science, academia, business, and public service in a continually changing world. To do this, the curriculum focuses on developing an ability to synthesize and apply knowledge from the many subjects studied to the design of systems, components, processes, or experiments, subject to technical, economic, environmental, and/or social constraints. Problems illustrating the design process are integrated into the core courses.

Freshmen normally take the core courses in mathematics, physics, chemistry, and biology (Ma 1 abc, Ph 1 abc, Ch1 ab, and Bi 1).

Sophomores take ordinary differential equations (Ma 2), wave physics (Ph 2a), chemistry laboratories (Ch 3a [or Ch 3x], and Ch/ChE 9). They also take the second-year organic chemistry course Ch 41 abc, and the basic chemical engineering courses (ChE 15, ChE 62, and ChE 63ab). The third-year applied and computational mathematics course (ACM 95ab) may be taken in the junior or sophomore years.

Undergraduate research is emphasized, and students are encouraged, even in the freshman year, to participate in research with the faculty. In order to obtain a basic intellectual background, all students take courses in the fundamentals of chemical engineering through the junior year. During the junior and senior years, students diversify into one of four tracks (biomolecular, environmental, materials, or process systems), where they pursue concentrated study in their chosen area of chemical engineering. An optional senior thesis provides an opportunity to pursue independent research and design in lieu of one of the senior laboratories.

Attention is called to the fact that any student whose gradepoint average is less than 1.9 at the end of an academic year in the subjects listed under the Division of Chemistry and Chemical Engineering may, at the discretion of the faculty in this division, be refused permission to continue the work in this option.

Option Requirements

1. Ma 2, Ph 2 a, Ch/ChE 9, ChE 15, Ch 21 abc, Ch 41 abc, ChE 62, ChE 63 ab, Ch/ChE 91 (or En 84), ACM 95 ab, ChE 101, ChE 103 abc, ChE 105, ChE 126, three science/engineering electives (two if ChE 90 ab is selected), and one of Ec 11[1], BEM 102, or BEM 103[1].
2. Completion of a track (biomolecular, environmental, process systems, or materials), each consisting of eight science or engineering courses (72 units, including 63 units of engineering courses). Students should inform the executive officer of their track choice by the beginning of the spring quarter of the sophomore year by providing a planned schedule for completion of all degree requirements. Requirements for the tracks are as follows.
   a. Biomolecular track: ChE/BE 163, Bi/Ch 110, [ChE 130 or ChE 90 ab], and 45 units of additional bioengineering or biochemical engineering electives. ChE 118 and/or ChE 120 may be elected provided the design project undertaken contains a significant biological component.
   b. Environmental track: two of the core ESE courses [ESE 101, 102, and 103], [ChE 128 or ChE 90 ab], 45 units of additional ESE or related courses. ChE 118 and/or ChE 120 may be elected provided the design project undertaken contains a significant environmental component.
   c. Process systems track: ChE 118, ChE 120,[ChE 128 or ChE 90ab], 45 units of engineering electives or courses from the other tracks.
   d. Materials track: ChE 128 or ChE 90 ab; one course on materials synthesis or processing selected from Ch/ChE 147[2], ChE 115[2], or MS 133; at least one course on the physical basis of structure and properties selected from Ch 120, ChE/Ch 148[2], MS 115, MS/APh 122, MS 131, or MS 132 and 45 units of additional chemical engineering or materials science elective courses selected from ChE 118, ChE 120, ChE/Ch 155[2], ChE/Ch 164, ChE/Ch 165, or any MS course.
3. Passing grades must be earned in all courses required by the Institute and the option. None of the courses satisfying option requirements may be taken pass/fail.
4. Passing grades must be earned in a total of 515 units, including courses listed above.

[1] *The 9 units of Ec 11 or BEM 103 partially satisfy the Institute requirements in humanities and social sciences.*

[2] *Given in alternate years.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2	Ordinary Differential Equations	9	-	-
Ph 2 a	Sophomore Physics: Waves	9	-	-
ChE	Introduction to Chemical Engineering Computations	-	9	-
Ch/ChE 9	Chemical Synthesis and Characterization for Chemical Engineering	-	-	9
Ch 41 abc	Organic Chemistry	9	9	9
ChE 62	Separation Processes	9	-	-
ChE 63 ab	Chemical Engineering Thermodynamics	-	9	9
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	HSS electives	-	9	9
		36	48	48
Third Year				
ChE 103 abc	Transport Phenomena	9	9	9
ChE 101	Chemical Reaction Engineering	-	9	-
ChE 105	Dynamics and Control of Chemical Systems	-	-	9
Ch/ChE 91	Scientific Writing	-	3	-
	ChE, Ch, track courses, and electives[1]	18	9	9
Ec 11, BEM 102, or BEM 103		9	-	-
PE	Physical Education	3	-	-
	HSS electives	9	18	18
		48	48	45
Fourth Year				
ChE 126	Chemical Engineering Lab	9	-	-
	ChE, Ch, track courses, and electives[1]	9	9	9
Ch 21 ab[2]	Physical Chemistry	9	9	9
	Science or Engineering electives	-	9	9
	HSS electives	9	9	9
		36	36	36

1 See option requirements.

2 Ch 24 a can be substituted for Ch 21 b.

Chemistry Option

The objective of the undergraduate option in chemistry is to produce graduates articulate in the fundamental concepts of the molecular sciences through a combination of coursework and laboratory experiences. The chemistry program at Caltech provides depth in the traditional areas of chemistry—organic and inorganic chemistry, chemical physics, theoretical chemistry, chemical biology, and biochemistry. Breadth in the program is found within the advanced coursework offerings and the specialized interests of the faculty, which may include topics such as: chemical synthesis and catalysis, chemical dynamics and reaction mechanisms, biochemistry, bioinorganic, bioorganic, and biophysical chemistry, and materials chemistry. Chemical research at Caltech is highly interdisciplinary, reflecting the increasing importance of molecular understanding to many fields of science. Major initiatives are fostering broad collaborations in energy and environment, molecular medicine, and nanomaterials. The outcome of the undergraduate program in chemistry is to prepare students for advanced graduate study and ultimately careers in teaching and research at colleges and universities, in research for government and industry, in the operation and control of manufacturing processes, and in management and development positions in the chemical industry.

A first-year general chemistry course is taken by all freshman students. The emphasis is on fundamental principles and their use in systematizing descriptive chemistry. The student's qualifications for placing out of Ch 1 ab will only be determined by the performance on a placement examination to be administered in the summer prior to registration. Students who did not pass the placement exam may take Ch 1 and Ch 41 simultaneously, but Ch 1 ab must be passed to satisfy the Institute chemistry requirement. The one-term required laboratory course (Ch 3 a) presents basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. The laboratory in the following two terms (Ch 4 ab), normally taken concurrently with Ch 41, introduces the student to methods of synthesis, separation, and instrumental analysis used routinely in research. Qualified students, with the instructor's consent, are allowed to substitute either Ch 4 a, Ch 8, or Ch/ChE 9 for the core requirement of Ch 3 a. Freshmen intending to major in chemistry are encouraged to take Ch 10 abc, which provides an introduction to research activities and opportunities in chemistry for undergraduates.

Beyond the freshman year, each student in the chemistry option, in consultation with his or her adviser, selects a suitable course of study under the supervision of the division. The requirements of the option are listed below. A student wishing to deviate from these requirements should submit an alternate curriculum, with justifications, for consideration by his or her adviser and the Chemistry Curriculum and Undergraduate Studies Committee. The chemistry option representative should be consulted for the future scheduling of courses not offered during the current academic year.

Undergraduates in the option must also take chemistry courses below the 100 level for a letter grade with the exception of the following courses, which are only offered on a pass/fail basis: Ch 1, Ch 3 a, Ch 90, and, if taken during the first or second terms of the freshman year, Ch 4 ab, Ch 21 ab, Ch 24, and Ch 41 ab.

Senior Thesis

Students attempting a senior thesis in the chemistry option must complete the following requirements.

1. Three terms (27 units) of Ch 82 are to be completed during the

junior and/or senior year of study; continued work from research experiences prior to the commencement of the senior thesis is encouraged.

2. At the time of registering for the first term of Ch 82, the candidate will submit a short (five-page) proposal delineating his/her project for approval by the research mentor and the Chemistry Curriculum and Undergraduate Studies Committee (CUSC).
3. The candidate will present a short progress report (maximum of five pages) at the end of each of the first two terms of Ch 82, describing the current status of the research work and any results obtained. Upon evidence of satisfactory effort, the student will be allowed to continue his/her senior thesis.
4. A thesis of approximately 20 pages (excluding figures and references) will be presented to the mentor and the CUSC at the end of the third term of Ch 82. An oral thesis defense will be arranged by the CUSC. The thesis must be approved by both the research mentor and the CUSC.
5. Upon approval by the research mentor and the CUSC, the Ch 91 requirement for graduation may be satisfied by the written thesis and the progress reports from the first two quarters of Ch 82. If the thesis is being completed during the spring quarter of the senior year, a draft of the thesis is to be submitted by Add Day.

Double Majors
For students simultaneously pursuing a degree in a second option, courses taken as *required* courses for that option can also be counted as chemistry electives (requirement 3, below) where appropriate. However, courses that count toward the electives requirement in the other option cannot simultaneously be counted toward satisfying the elective requirement in chemistry.

The courses listed below would constitute a common core for many students in the option.

Any student of the chemistry option whose grade-point average is less than 1.9 will be admitted to the option for the following year only with the special permission of the Division of Chemistry and Chemical Engineering.

Option Requirements

1. Ch 14, Ch 21 abc (or Ch 21a, Ch 24, and Ch 25), Ch 41 abc, Ch 90, Ma 2, and Ph 2a. Ma 3 recommended but not required. For students taking a full year of physics (Ph 2abc or Ph 12abc), the physical chemistry requirement can be satisfied by passing either Ch 21b or Ch 24. Students with the appropriate background upon completion of Ph 2a or Ph 12a may substitute the following 100-level courses for Ch 21a (Ch 125a or Ph 125a); Ch 21b (Ch 125b, Ch 126, Ph 103, or Ge 132); and Ch 21c (ChE/Ch 164 or Ph 127a). 100-level courses used in substitution for Ch 21abc may not also be counted towards the five terms of advanced chemistry electives.

2. A minimum of five terms of laboratory work chosen from Ch 4ab, Ch 5ab, Ch 6ab, Ch 7, Ch 10c (if taken freshman or sophomore year), and Ch 15. One non-chemistry laboratory course may be used, chosen from Bi 10, MS 90, Ph 6 and Ph 7.
3. A minimum of five terms of advanced chemistry electives (which must total at least 45 units) taken for a letter grade from chemistry course offerings at the 100 and 200 level, including cross-listed offerings, but excluding Ch 180 and Ch 280.
4. Passing grades must be earned in the courses that constitute the approved program of study, including those listed above. None of the courses satisfying option requirements may be taken pass/fail.
5. The chemistry option strongly encourages students to engage in academic year research, and up to 27 units each of Ch 80 and Ch 82 will toward towards the 486-unit requirement.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ch 41 abc	Organic Chemistry	9	9	9
Ma 2	Sophomore Mathematics	9	-	-
Ph 2 a	Sophomore Physics	9	-	-
Ch 4 ab	Synthesis and Analysis of Organic and Inorganic Compounds	-	9	9
Ch 14	Chemical Equilibrium and Analysis	-	-	6
	Electives	18-21	18-27	21-24
		45–48	36-45	45–48
Third Year				
Ch 5 a	Advanced Techniques of Synthesis and Analysis	-	12	-
or				
Ch 5 b		9	-	-
Ch 15	Chemical Equilibrium and Analysis Laboratory	10	-	-
Ch 21 abc	Physical Chemistry	9	9	9
or				
Ch 21 a, Ch 24, Ch 25				
Ch 90	Oral Presentation	-	3	-
Ch/ChE 91	Scientific Writing	-	-	3
	Electives	17-29	21-36	33-36
		45–48	45–48	45–48
Fourth Year				
Ch 6 a	Physical and Biophys. Chemistry Lab			
or		-	10	-
Ch 6 b		-	-	10
or				
Ch 7	Advanced Experim. Methods in Bioorganic Chemistry	-	-	9
	Electives	45–48	35–48	26–48
		45–48	45–48	45–48

This typical program is not specifically required for graduation in the option, nor is it in any sense a complete program. Students are expected to work out individual programs suitable for their interests and professional goals in consultation with their advisers. Several representative programs, including sets of possible electives, are shown below. These may well approximate choices by students who intend to do graduate work in conventional areas of chemistry.

Suggested Representative Courses of Study for Those Intending Graduate Work in Particular Areas of Chemistry

	Second Year	*Third Year*	*Fourth Year*
Inorganic Chemistry	Ch 4 ab, Ch 5 a, Ch 41 abc, Ch 102, Ma 2 ab, Ph 2 ab, HSS elective, other elective	Ch 5 b, Ch 14, Ch 21 abc, Ch elective(s), Ch laboratory, Ch 80, Ch 90, Ch/ChE 91, HSS elective	Ch 6 a or 6 b, Ch electives, Ch 80, HSS elective
Chemical Physics	Ch 4 ab, Ch 21 abc, Ch 6 ab, Ch 14, Ma 2 ab, Ph 2 ab, HSS elective	Ch laboratory, Ch 41 abc, Ch elective(s), Ch 80, Ch 90, ACM 95 abc, Ch/ChE 91, HSS elective	Ch 125 abc, Ch electives, Ch 80, HSS elective
Organic Chemistry	Ch 4 ab, Ch 5 a, Ch 41 abc, Ch 102, Ma 2 ab, Ph 2 ab, HSS elective, other elective	Ch 5 b or Ch 7, Ch 14, Ch 21 abc, Ch elective(s), Ch laboratory, Ch 80, Ch 90, Ch/ChE 91, HSS elective	Ch 6 a or Ch 6 b, Ch electives, Ch 80, HSS elective
Biochemistry	Ch 4 ab, Bi 10, Ch 41 abc, Bi 9, Ma 2 ab, Ph 2 ab, HSS elective	Ch laboratory, Ch 7, Ch 14, Ch 21 a, Ch 24, Ch 25 (or Ch 21 bc), Ch 80 (or Bi 22), Ch 90, Ch/ChE 91, Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi 10,	Ch 6 a or 6 b, Ch (Bi) electives, Ch 80 (or Bi 22), HSS elective

Computer Science Option and Minor

Study in the computer science option within the Computing & Mathematical Sciences department emphasizes rigor and creativity, and is good preparation either for graduate study followed by a research career, or for a variety of professional or entrepreneurial occupations.

The option introduces students to the mathematical and engineering foundations of the discipline. It provides considerable flexibility in course selection, together with a capstone project giving an opportunity for independent work in an area of the student's choice. Individual programs will be worked out in consultation with faculty advisers (the materials at www.cs.caltech.edu/academics/undergrad_study.html may be helpful for this purpose).

Any student in the computer science option whose grade-pointaverage is less than 1.9 at the end of the academic year in the subjects listed in the option requirements may be refused permission to continue work in the option.

Double Majoring Requirement
Students interested in simultaneously pursuing a degree in a second option must fulfill all the requirements of the computer science option. Courses may be used to simultaneously fulfill requirements in both options. However, it is required that students have at least 63 units of computer science courses numbered 80abc, 81abc, or 114 and above that are not simultaneously used for fulfilling a requirement of the second option, i.e., requirement 4 in computer science must be fulfilled using courses that are not simultaneously used for fulfilling a requirement of the second option. To enroll in the program, the student should meet and discuss his/her plans with the option representative. In general, approval is contingent on good academic performance by the student and demonstrated ability for handling the heavier course load.

Option Requirements

1. *CS fundamentals.* CS 1; CS 2; CS 4; CS 11,
2. *Intermediate CS.* CS 21; CS 24; CS 38.
3. *CS Project Sequence.* One of the following:
   a. An undergraduate thesis (CS 80abc) supervised by a CS faculty member.
   b. A project in computer science, mentored by the student's academic adviser or a sponsoring faculty member. The sequence must extend at least two quarters and total at least 18 units of CS 81abc.
   c. Any of the following three-quarter sequences. Each of the sequences is expected to be available (nearly) yearly.
      i. Databases: CS 121, CS 122, CS 123.
      ii. Graphics: CS/CNS 174 and two other CS 17x courses.
      iii. Learning & Vision: At least three courses chosen from ME/CS 132 ab, EE/CNS/CS 148, CMS/CS/CNS/EE 155, CS/CNS/EE 156 ab, CS/CNS/EE 159, CNS/Bi EE/CS 186, CNS/Bi/Ph/CS 187, ACM/CS/EE 218, including at least one of 132 b, 148, 156 b, 159, or 186.
      iv. Networking & Distributed Systems: CS/EE 145 combined with two courses chosen from CS 142, CS/EE 143, and CS/EE 144.

v. Quantum & Molecular Computing: At least three courses chosen from BE/CS/CNS/Bi 191 ab, BE/CS 196 ab, BE ChE 130, Ph/CS 219 abc.

vi. Robotics: At least three courses chosen from ME 115 ab, ME/CS 131, ME/CS 132 ab, EE/CNS/CS 148, CNS/ Bi/EE/CS 186.

4. Advanced CS. A total of 72 CS units that are not applied to requirements 1 or 2 above,
   and that either (i) are numbered CS 114 and above or (ii) are in satisfaction of requirement 3 above. Included in these units must be at least one of CS 122, CS 124, CMS/CS 139, or CS 151.
5. *Mathematical fundamentals.* Ma 2; Ma 3; Ma/CS 6a or Ma 121a.
6. *Communication fundamentals.* E10; E11.
7. *Scientific fundamentals.* In addition to all above requirements, 18 units selected from the following courses Bi 8, Bi 9, Ch 21abc, Ch 24, Ch 25, Ch 41abc, Ph 2abc, Ph 12abc, or any 100+ course in Bi, Ch, or Ph.
8. *Breadth.* In addition to all above requirements, 36 units in Ma, ACM, or CS; 18 units in EAS or Ma; and 9 units not labeled PE or PA.

Units used to fulfill the Institute Core requirements do not count toward any of the option requirements. Pass/fail grading cannot be elected for courses taken to satisfy option requirements. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
	Scientific Fundamentals	9	9	-
Ma 2 , Ma 3	Sophomore Mathematics	9	9	-
CS 1	Intro. to Computer Programming[1]	9	-	-
CS 2	Intro. to Programming Methods[1]	-	9	-
CS 4	Fundamentals of Computer Program.	-	9	-
Ma/CS 6 a	Intro. to Discrete Math	9	-	-
CS 21	Decidability and Tractability	-	9	-
CS 24	Intro. to Computing Systems	-	-	9
CS 38	Introduction to Algorithms	-	-	9
	HSS electives	9	-	9
	Other electives	-	-	9
		45	45	36
Third Year				
	CS courses	9	9	9
	CS project	9	9	9

	HSS electives	9	9	9
E 10	Technical Seminar Presentations	-	-	3
	EAS/Ma courses	9	9	9
	Other electives	9	9	-
		45	45	39
Fourth Year				
	CS courses	9	-	-
	HSS electives	9	18	9
	EAS/Ma courses	9	9	9
	Other electives	18	9	18
		45	36	36

[1] *Commonly taken during the freshman year.*

Computer Science Minor

The computer science minor is intended to supplement one of Caltech's undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major or who may wish to pursue a graduate program involving computer science. Students completing the computer science minor requirements will have the phrase "minor in computer science" added to their transcripts.

Minor Requirements

Computer Science Minor Requirements

1. *CS fundamentals.* CS 1; CS 2; and CS 11.
2. *Mathematical fundamentals.* Ma 2; Ma 3; Ma/CS 6a or Ma 121a.
3. *Intermediate CS.* CS 21; CS 24; CS 38.
4. *Advanced CS.* 9 CS units numbered 114 or above that are not applied to the above requirements and are not simultaneously used for fulfilling a requirement of the student's major option. Pass/fail grading cannot be elected for courses taken to satisfy option requirements. Courses taken as part of the computer science minor are counted toward the total 486 units needed for Institute graduation requirements. To enroll in the program, the student should meet and discuss his/her plans with the option representative. In general, approval is contingent on good academic performance by the student and demonstrated ability for handling the heavier course load.

Control and Dynamical Systems Minor

Control and dynamical systems (CDS) may be pursued as a minor concentration by undergraduates who are taking degrees in science, mathematics, or engineering. The CDS minor is intended to supplement one of Caltech's normal undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major or who may wish to pursue a graduate program involving control or dynamical systems. Students completing the minor requirements below in CDS will have the phrase "minor in control and dynamical systems" added to their transcripts and their graduating degree materials.

CDS Minor Requirements

1. Complete CDS 110 and CDS 140.
2. Complete nine additional units in CDS courses, chosen from CMS/ACM 116, CDS 112, CDS 212 or CDS 240.
3. Complete a three-term senior thesis approved by the CDS faculty.

All CDS courses to be applied to fulfill the CDS minor requirements must be taken for grades, and students must obtain a grade of B or higher. The senior thesis requirement may be satisfied by completing a three-term senior thesis in the student's major option but on CDS subject matter, with the approval of the thesis topic by the CDS option representative, or by taking CDS 90 abc.

Courses that are used to satisfy the CDS minor cannot be used to satisfy course requirements in the major options, with the exception that CDS 110 may be used in EAS options where this is part of their requirements (e.g., ChE, EE, ME) and the senior thesis requirement may be used to satisfy requirements for major options that require a senior thesis. Courses taken as part of the CDS minor are counted toward the total 486 units needed for Institute graduation requirements.

A typical course sequence would be to take either CDS 110 or CDS 140 in the junior year, followed by the remaining courses and the senior thesis in the senior year. Alternatively, it is possible to take all requirements in the senior year. In addition to the requirements above, CS 1 and CS 2 are highly recommended.

Economics Option

The economics option provides students with an understanding of the basic principles underlying the functioning of economic institutions. It offers a modern and quantitative approach to economics seldom available to undergraduates. The emphasis on economic principles and modern methodology provides students with an excellent preparation for graduate study in economics or for professional study in the fields of business, law, or economics.

The option is sufficiently flexible that students can combine their pursuit of economics with studies in engineering, mathematics, or science. The core of the option consists of an economic theory component, a data analysis component, an applied microeconomic component, and a macroeconomic/growth component. Students are strongly encouraged to supplement this core with additional electives in economics, political science, and mathematics.

Option Requirements

1. Ec 11.

2. Theory: Ec 121 ab and PS/Ec 172.
3. Data analysis: Ec 122.
4. Applied microeconomics: one of Ec 105, BEM/Ec 118, Ec 133, Ec 135, or Ec 145.
5. Macroeconomics and growth: one of Ec 123, Ec/SS 129, 130, or Ec 140.
6. Ma 3.
7. 45 additional units of advanced economics and social science courses. (Courses that are used to fulfill the Institute advanced social science requirement [courses numbered 100 and above] will also count toward this requirement.) Students may also take classes from the following list in partial fulfillment of this requirement: any BEM course except BEM 102; ACM 113 and ACM 116.
8. 45 additional units of advanced science, social science, mathematics, and engineering courses. The requirement cannot be satisfied by any course with a number less than 100.
9. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.
10. Writing/oral presentation courses: a scientific writing requirement course, and a three-unit course in oral communication, offered by any division (some options combine these two requirements into one course, that can be taken to satisfy this requirement), or En/Wr 84. The course used to satisfy this requirement must be taken on grades.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 3	Sophomore Mathematics	-	9	-
	Menu Course	-	-	9
Ec 11	Introduction to Economics	9	-	-
PS 12	Introduction to Political Science	-	-	9
	Electives[1]	27	27	27
		36	36	45
Third Year				
Ec 105	Industrial Organization	-	9	-
Ec 121 ab	Theory of Value	9	9	-
PS/Ec 172	Game Theory	-	-	9
Ec 122	Econometrics	9	-	-
Ec 123	Macroeconomics	-	-	9
	Electives[1]	27	27	27
		45	45	45
Fourth Year				
En/Wr 84 or a scientific writing requirement course, and a three-unit course in oral communication,		-	-	9

Electives[1]	45	45	36
	45	45	45

[1] *See option requirements 5 and 7.*

Electrical Engineering Option

The objective of the undergraduate program in Electrical Engineering at Caltech is to produce graduates who will attain careers and higher education that ultimately lead to leadership roles in academia, industry and government in areas of rapidly advancing interdisciplinary technology related to telecommunications, solid-state, information, computer and electrical systems.

The program prepares its students for either graduate study, entrepreneurial careers, or research and development work in government or industrial laboratories. It inspires them to undertake careers and professional practices that provide an opportunity to address the pressing technological needs of society. It accomplishes this by building on the core curriculum to provide a broad and rigorous exposure to the fundamentals (e.g., math, science, and principles of engineering) of electrical engineering. EE's other program objectives are multiple. The program strives to maintain a balance between classroom lectures and laboratory and design experience, and it emphasizes the problem formulation, system-design, and solving skills that are essential to any engineering discipline. The program also strives to develop in each student self-reliance, creativity,teamwork ability, professional ethics, communication skills, and an appreciation of the importance of contemporary issues and lifelong intellectual growth. For interested students, there are opportunities to conduct research with a faculty member.

Students electing this option normally choose to take the introductory seminar EE 1 as a freshman-year elective. The formal study of electrical engineering begins in the sophomore year with circuits and systems, EE 44; digital electronics, EE/CS 51, 52ab; semiconductor sensors and actuators, EE 40; the theory and laboratory practice of analog circuits, EE 45; and then a course on feedback control systems, EE 113 or CDS 110 a. The junior year features the fundamentals of signals and systems and digital signal processing, EE 111; random variables and stochastic processes, EE 160; electromagnetic engineering, EE 151; and an analog electronics laboratory, EE 90. In the senior year, the student will be asked to demonstrate his or her ability to formulate and carry out a design project through independent research or either a senior thesis, EE 80 abc, or two courses selected from the senior project design laboratory, EE 91 ab, EE/CS 53, and CS/EE/ME 75 c. In addition, the student, especially in the senior year, will have a significant opportunity to take elective courses that will allow him/her to explore earlier topics in depth, or to investigate topics that have not been covered previously. (See the "suggested electives" section, page 257.)

A student whose interests lie in the electrical sciences but who wishes to pursue a broader course of studies than that allowed by the requirements of the electrical engineering option may elect the engineering and applied science option.

Attention is called to the fact that any student who has a grade-point average less than 1.9 at the end of the academic year in the subjects listed under electrical engineering may be refused permission to continue work in this option.

Double Majors

The electrical engineering option allows interested students to declare electrical engineering as one of the majors in a double major pursuit. To enroll in the program, the student should meet and discuss his/her plans with the option representative. In general, approval is contingent on good acadamic performance by the student and demonstrated ability for handling the heavier course load. For students simultaneously pursuing a degree in a second option, courses taken as required courses for that option can also be counted as EE electives where appropriate. However, courses that count toward the electives requirement in the other option cannot be simultaneously counted toward satisfying the elective requirement in EE. To qualify for an EE degree, the student would need to complete all option requirements.

Option Requirements

1. Ma 2, Ma 3, Ph 2 abc.
2. APh/EE 9 a or APh 109.
3. EE 1, E 10, E 11, EE 40, 44, 45, EE/CS 51, 52 ab, EE 90, 111, 151, and 160.
4. ACM 95 ab
5. EE 113 or CDS 110.
6. One of EE 112, EE 126 a, EE 127, or EE 163 a.
7. One term of EE 91.
8. EE 80 abc, or a sequence consisting of CS/EE 143, 144, 145, or a sequence consisting of BE/EE/MedE 189 a, or one course selected from an additional term of EE 91, EE/CS 53, EE 119 c, and CS/EE/ME 75 c (note that CS/EE/ME 75 ab does not satisfy this requirement).
9. In addition to the above courses, 27 units selected from any EE course numbered over 100, or any cross-listed courses numbered over 100 that include EE in the listing.
10. Passing grades must be earned in a total of 486 units, including courses listed above.

Typical Course Schedule[1]

		Units per term 1st	2nd	3rd
Second Year – Schedule 1				
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2, Ma 3	Sophomore Mathematics	9	9	-
	HSS electives[1]	9	9	9
EE 40	Introduction to Semiconductors and Sensors	-	-	9
EE 44	Circuits and Systems	12	-	-
EE 45	Electronics Laboratory	-	12	-
EE 113	Feedback and Control Systems	-	-	9
EE/CS 51	Principles of Microprocessor Systems	12	-	-
EE/CS 52 ab	Microprocessor Systems Laboratory	-	9	6
	Electives	-	-	9
		51	48	51
Second Year – Schedule 2				
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2, Ma 3	Sophomore Mathematics	9	9	-
	HSS electives	9	9	9
EE 40	Introduction to Semiconductors and Sensors	-	-	9
EE 44	Circuits and Systems	12	-	-
EE 45	Electronics Laboratory	-	12	-
EE 113	Feedback and Control Circuits	-	-	9
ACM 95 ab	Intro. Methods of Applied Math.	9	12	-
	Electives	-	-	12
		48	51	48
Third Year – Schedule 1				
E 10	Technical Seminar Presentations	3	-	-
E 11	Written Technical Communication	-	3	-
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	HSS electives[1]	9	9	9
EE 151	Electromagnetic Engineering	-	9	-
EE 111	Signals, Systems, and Transforms	9	-	-
EE 90	Analog Electronics Project Lab	-	-	9
EE 160	Random Variables and Stochastic Processes	9	-	-
	Electives	9	9	18
		39	42	48
Third Year – Schedule 2				
E 10	Technical Seminar Presentation	3	-	-
E 11	Written Technical Communication	-	3	-
EE/CS 51	Principles of Microprocessor Systems	12	-	-
EE/CS 52 ab	Microprocessor Systems Laboratory	-	9	6
	HSS electives	9	9	9
EE 151	Electromagnetic Engineering	-	9	-
EE 111	Signals, Systems, and Transforms	9	-	-
EE 90	Analog Electronics Project Lab	-	-	9

EE 160	Random Variables and Stochastic Processes	9	-	-
	Electives	-	18	18
		42	48	42

Fourth Year (for project)

	HSS electives[1]	9	9	9
EE 91 ab[2]	Experimental Projects in Electronic Circuits	12	-	-
	EE electives	9	9	9
	Electives	9	18	18
		39	36	36

Fourth Year (for thesis)

	HSS electives[1]	9	9	9
EE 91 ab[2]	Experimental Projects in Electronic Circuits	12	-	-
EE 80	Senior Thesis	9	9	9
	EE electives	9	9	9
	Electives	3	9	9
		42	36	36

[1] *See Institute requirements for specific rules regarding humanities and social sciences.*
[2] *See option requirements 4 and 5.*

Suggested Electives

First-year students interested in electrical engineering should consider taking APh/EE 9 a (or APh 109 later), which is an EE option requirement (though it need not be taken freshman year).

Suggested elective courses for the second, third, and fourth year for various specializations within electrical engineering are given below. Students interested in other areas of specialization or interdisciplinary areas are encouraged to develop their own elective program in consultation with their faculty adviser.

Bioengineering
Second Year: Bi 9, Bi 10, APh 17 abc.
Third and Fourth Year: Bi/Ch 110, Bi/Ch 113, EE/MedE 114, BE 141, EE/BE/MedE 166, EE/BE/MedE 185, CNS/Bi/EE/CS/NB 186, CNS/CS/EE 188, BE/EE/MedE 189 ab.

Communications and Signal Processing
Second Year: Selected from APh 17 abc, APh 23, APh 24, EE/CS 53.
Third and Fourth Year: EE 112, EE/Ma 126 ab, 127 ab, EE 128 ab, 161, 163 ab, 164, 167, EE/APh 131, APh/EE 130, 132, Ma 112 a.
Control
Second Year: APh 17 abc.
Third and Fourth Year: CDS 110, and selections from EE 112, EE 128 ab, EE 164.

Electronic Circuits
Second Year: EE 113, CDS 101, APh/EE 183.
Third and Fourth Year: EE/MedE 114 ab, 124, EE 125, 153, 119 ab, CS/EE 181 abc, and selections from EE 112, CS 185 abc, EE/APh 180, EE 119, EE 160, EE 128 ab.

Microwave and Radio Engineering
Second Year: APh 23, APh 24, APh 17 abc.
Third and Fourth Year: EE 153, EE/Ae 157 ab, EE/MedE 114 ab, EE/APh 131, APh/EE 130, 132, APh/EE 183.

Optoelectronics
Second Year: APh 23, APh 24, APh 17 abc.
Third and Fourth Year: APh/EE 130, 132, APh 105 abc, APh 114 abc, APh/EE 183, APh 190 abc, EE/APh 131, EE 153.
Solid-State Electronics and Devices
Second Year: APh 17 abc.
Third and Fourth Year: APh/EE 183, and selections from APh 105 abc, APh 114 ab, EE 153, EE/BE 185, EE/MedE 187.

Engineering and Applied Science Option

The engineering and applied science (EAS) option offers students the opportunity for study in a wide variety of challenging areas of science and technology and includes concentrations in computation and neural systems, and materials science. In addition, the EAS option offers students the possibility of designing a customized course of study that has breadth, depth, and rigor similar to the concentrations listed above.

The aim of the EAS option is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program builds on the core curriculum to combine individual depth of experience and competence in a particular chosen engineering specialty, and a strong background in the basic and engineering sciences, with laboratory and design, culminating in a capstone design experience. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

The first year of the four-year course of study leading to a Bachelor of Science degree is common for all students of the Institute, although freshman elective subjects are available as an introduction to various aspects of engineering and applied science. At the end of the first year, students who elect the EAS option are assigned advisers as close to their expressed field of interest as possible, and together with their advisers they develop programs of study for the next three years. Beyond the Institute-wide requirements of physics, mathematics, and humanities, the EAS option requires one year of applied and computational mathematics and a prescribed number of units selected from a wide variety of engineering and applied science courses. Engineering design (synthesis), as distinct from analysis, is considered an essential part of every engineer's capability. Advisers will expect students to select a sufficient number of courses that place emphasis on design.

Any student in the EAS option whose grade-point average is less than 1.9 at the end of the academic year in the subjects listed in the option requirements may be refused permission to continue to work in the EAS option.

Option Requirements

Students who have elected the EAS option must either choose one of the approved areas of concentration (see item 6 a below), or by the end of the third term of the sophomore year submit a written proposed customized course of study and obtain approval for it from the EAS option oversight committee (see item 6 b below).

The course of study must include each of the following elements:

1. Fulfillment of core requirements in differential equations (Ma2 or equivalent); Probability and Statistics (Ma3, ACM/ESE118 or equivalent); Waves (Ph2a, Ph12a or equivalent), Quantum Mechanics (Ph2b, Ph12b, Ch21a or equivalent); Thermodynamics and Statistical Mechanics (Ph2c, Ph12c, ChE63, ME11, Ch21c or equivalent)
2. Demonstration of computer programming competency by taking CS 1, or by taking an approved alternative course, or by passing a placement exam administered by the computer science option by first term of sophomore year.
3. a. 27 units of advanced EAS courses with the prefixes Ae, ACM, AM, APh, BE, CE, CNS, CS, CDS, EE, ESE, MS, or ME;
   and
   b. 27 additional units of either advanced EAS courses or advanced science courses offered by the biology, CCE, GPS, or PMA divisions.
4. a. 9 units of laboratory courses taken from the following list: APh 77 bc, Ae/APh 104 bc, CE 95, CE 180, CS/CNS 171, 173, and 174, EE 45, EE/CS 52 ab, 53, 54, EE 90, EE 91 ab,ESE 159, MS 90, MS 125, ME 72 ab, ME 90 bc, ME 96; and
   b. 9 units of additional laboratory courses either from the list in 3 a or from EAS courses with the word “laboratory” in the title, but excluding those courses for which freshman laboratory credit is allowed.
5. ACM 95 ab or Ma 108 abc or Ma 109 abc. None of these course sequences may be taken pass/fail.
6. E 10 or equivalent; E 11 or equivalent.
7. Courses used to satisfy requirements 1–5 above must also satisfy a depth requirement, which must be met by either:
   a. the concentration requirements listed below for one of the following disciplines: computation and neural systems, and materials science,
   or
   b. a customized schedule of requirements that is similarly

rigorous to 6 a, has both breadth and depth, and that includes a senior thesis or capstone design project, such as, but not restricted to, EE 80 abc, CS 80 abc, ME 90 abc, or two terms chosen from EE 91 ab and EE/CS 53. To select this alternative, the student must submit a written proposal to, and obtain the approval of, the EAS option oversight committee. This approval must be obtained by the end of the third term of the sophomore year.

(Note: Students who meet the depth requirement by satisfying one of the five concentration requirements listed in 6 a will have both the EAS option and the name of the concentration listed on their transcript, while students who satisfy the depth requirement using 6 b will have only the EAS option listed on their transcript.)

8. At least 117 units of EAS courses not including those used to satisfy requirements 3, 4, and 5 above. Concentrations marked with a dagger (†) in the list below include sufficient EAS courses to automatically satisfy this requirement; concentrations marked with an asterisk (*), and also the customized schedule given in 6 b, do not do so, in which case students will have to select sufficient additional EAS courses to bring the total to 117 units. Courses in ChE count toward this requirement.
9. All concentrations and the customized schedule of requirements described in 6 b shall include a major design experience.
10. Passing grades must be earned in at least 486 units, including those listed in requirements 1–8 above.

Discipline Concentration Requirements (to satisfy requirements 6 a and 8 above)

*Computation and Neural Systems**

CNS 100, ACM 11, Bi/CNS/NB 150, Bi/CNS/NB 153, Bi/CNS/NB 157, Bi/CNS/NB 164, BE/CS/CNS/Bi 191a, CNS/Bi/Ph/CS/NB 187, CNS/Bi/EE/CS/NB 186, EE 111, Bi 8 (or Bi 1x or Bi 9), Ph 2 abc, Ma 2, Ma 3 and CS 2 is required in addition to CS 1 for the CNS concentration. In addition, the laboratory course Bi/CNS 162 is required. The project for CNS/Bi/EE/CS/NB 186 shall be organized as a design project drawing on the ensemble of CNS disciplines.

Materials Science†

APh 17 ab or ChE 63 ab or ME 11 abc; MS 115 or MS/ME/MedE 116; MS 90; and three terms of MS 78 (senior thesis, which includes a major design experience). In addition, the student shall complete 45 units from the following list of restricted electives: ME 12 abc, APh 105 abc, APh 114 abc, APh/EE 130, APh/EE 183, Ch 120 ab, Ch 121 ab, Ch 125 abc, Ch/ChE 147, ChE/Ch 148, CS 11, Ge 114 ab, MS 105, MS/APh 122, MS 125, 131, 132, 133, 142, Ph 125 abc. Substitution of courses may be approved at the discretion of the concentration representative, provided they meet the overall EAS requirements.

Typical Course Schedules

		Units per term		
		1st	2nd	3rd
Second Year				
	HSS electives	9	9	9
	Electives	36	36	36
		45	45	45
Third Year				
ACM 95 abc or Ma 108 abc or Ma 109 abc		12	12	12
	HSS electives	9	9	9
	Electives	24	24	24
		45	45	45
Fourth Year				
E 10	Technical Seminar Presentations	-	3	-
	HSS electives	9	9	9
	Electives	33	33	33
		42	45	42

Typical Course Schedules by Concentration

Variation of the course schedule from these examples should be made in consultation with the student's academic adviser and must satisfy the discipline concentration requirements listed above.

Computation and Neural Systems

	First Term	*Second Term*	*Third Term*
First Year	CS 1	CS 2 Bi 8	Elective
Second Year	CNS 100 EE 111 Bi/CNS/NB 150 Ma 2 Ph 2 a	Elective Ma 3 Ph 2 b	ACM 11 Ph2 c
Third Year		CNS 186[1] ACM 95 a	Bi/CNS 162[1] ACM 95 b
Fourth Year	CNS 187 E 10	Bi 153 Bi/CNS 164 BE/CS 191A	Bi 157

[1] *Offered biannually.*

Materials Science

	First Term	*Second Term*	*Third Term*
Second Year	APh 17 a MS 115	APh 17 b MS/ME/MedE 116	Restricted elective or MS 90

Third Year		ACM 95 a	ACM 95 b
	Restricted elective	Restricted elective	Restricted elective or MS 90
Fourth Year	MS 78 a MS 131 MS 132	MS 78 b E 10	MS 78 c MS 133

English Option and Minor

The option in English provides students with a broad education in English and American literatures, their historical contexts, and different approaches to their study. During the senior year, English majors will enroll in En 99 ab with a faculty member chosen by mutual agreement. En 99 a is devoted to research and En 99 b to writing a substantial research paper. This paper provides the most important means for evaluating a major's progress in the rigorous study of English. The English option provides excellent preparation for students seeking careers in law, business, administration, and medicine. The emphasis on writing critical essays helps scientists and engineers develop the communication skills necessary for success in their fields.

All students are assigned an adviser who will help them select the courses best suited to their needs, including courses in fields such as history that may be relevant for work in the English option. Students will be expected to consult their adviser before registering for each quarter's work. It is recommended that English majors take at least one English or related course per term. Those who are preparing for graduate work in English should take more than the minimum requirements listed below, and should be prepared to take courses in several periods of English and American literature. All courses to be counted toward the option in English must be taken for grades except for a freshman humanities course in English when taken in the first two quarters of the freshman year.

Option Requirements

1. En 99 ab.
2. 81 additional units of English courses numbered 99 and above. 27 of these units must include one course in British literature, one course in American literature, and one course in literature before 1850 (En 114, 122, 125, 129). Courses cannot be counted twice in meeting these distribution requirements. Up to nine units of Hum/En 5, Hum/En 6, or Hum/En 7 and/or up to nine units of En 98 may be substituted for up to 18 of the remaining 54 English units. Students may also substitute courses in foreign literature (in the original or in translation) and/or, with authorization of the adviser, related humanities courses numbered above 99, for up to 18 of the remaining 54 English units.
3. 54 additional units of science, mathematics, and engineering courses. This requirement cannot be satisfied by courses listed

as satisfying the introductory laboratory requirement or by a course with a number less than 10.

4. Passing grades must be earned in a total of 486 units, including the courses listed above.

Courses used to complete the English option under categories 1 and 2 above may not be used to satisfy the requirements of another option or minor. However, these courses may be used to satisfy core Institute requirements in the humanities.

English Minor Requirements

The English minor is designed for students who want to pursue concentrated study in English and/or American literature, without the extensive course work and the senior thesis required by the English option.

English minors must take 72 units of English courses. These units may include one freshman humanities course; they may also include one directed reading course (En 98). Students wishing to do a minor in English must declare a minor with the English option representative. All courses to be counted toward the option in English must be taken for grades except for a freshman humanities course in English when taken in the first two quarters of the freshman year. Students completing the English minor requirements will have the phrase "minor in English" added to their transcripts.

1. 72 units of English courses numbered 99 or above.
2. Nine units of Hum/En 5, Hum/En 6, or Hum/En 7 may be substituted for any nine of the 72 units required for the minor.
3. Nine units of En 98 may be substituted for any nine of the 72 units required for the minor.

Courses used to complete the English minor may not be used to satisfy the requirements of another option or minor. However, these courses may be used to satisfy core Institute requirements in the humanities.

Environmental Science and Engineering Minor

The ESE minor is intended to supplement one of Caltech's undergraduate degrees. It is designed for students who wish to broaden their studies beyond their major to include environmental science and engineering. Students completing the ESE minor requirements will have the phrase "minor in environmental science and engineering" added to their transcripts.

ESE Minor Requirements

1. Complete 27 units of ESE 1, 101, 102, or 103
2. Complete 27 additional units of ESE courses (which may include up to 18 units of research under ESE 90, including the required written report).

Except for research courses, all ESE courses to be applied to fulfill the minor requirements must be taken for grades, and students must maintain a minimum grade average of B- in this ESE coursework. Courses that are used to satisfy the ESE minor requirements cannot be used to satisfy course requirements in the major.

Geobiology, Geochemistry, Geology, Geophysics, and Planetary Science Options

The aim of this undergraduate program is to provide thorough training in the geological and planetary sciences and, wherever possible, to integrate these studies with courses in mathematics, physics, chemistry, and biology taken during the student's earlier years at the Institute. Active involvement in research, particularly during the summer, is encouraged. For geologists, field work is important because it provides firsthand experience with geological phenomena that can never be satisfactorily grasped or understood solely from classroom or laboratory treatment. Options are offered in geology, geobiology, geochemistry, geophysics, and planetary science. Electives permit students to follow lines of special interest in related scientific and engineering fields. Those who do well in the basic sciences and at the same time have a compelling curiosity about the earth and the other planets are likely to find their niche in these options, especially if they enjoy grappling with complex problems involving many variables. Most students majoring in the earth and planetary sciences now pursue further training at the graduate level.

Under the geobiology option, a student can be associated with either the biology or the GPS division. This association formally will only affect which course the students elect to satisfy the Institute-wide oral presentation requirement; all other geobiology option requirements are independent of GPS or biology affiliation. In practice, however, we expect that students' affiliation with one division or another will significantly shape their choice of elective courses.

For students beginning their junior year, it is possible to complete the requirements for geochemistry, geophysics, and planetary science options within two years, but there are benefits from starting with the Ge 11 sequence in the sophomore year. Because Ge 120 ab may not be offered every year, students in the geology option may also need to take Ge 106 and Ge 120 a in winter and spring term of their sophomore year in order to prepare for Ge 120 b the following summer.

Passing grades must be earned in a total of 486 units, including courses listed below. Any student whose grade-point average in science and mathematics courses is less than 1.9 at the end of an academic year may be refused permission to register in the geological and planetary science options.

Double Majors

For students simultaneously pursuing a degree in a second option, courses taken as required courses for that option can also be counted as

Ge electives where appropriate. However, courses that count toward the electives requirement in the other option cannot simultaneously be counted toward satisfying the elective requirement in GPS.

Option Requirements

Geology Option Requirements

1. Ge 11 ab, Ge/Ay 11 c or Ge 11 d[1], Ge 109, and any writing class that satisfies the Institute scientific writing requirement[2].
2. Ma 2 and one choice from: Ma 3, Ge/ESE 118, or Ge/Ay 117.
3. Ph 2 a or Ph 12 a plus an additional quarter of sophomore-level physics (Ph 2 b, 2 c, 12 b, or 12 c).
4. Either ACM 95 ab or the combination of a full-year chemistry sequence (Ch 41 abc or Ch 21 abc).
5. Ge 106, 114 ab, 115 ab, 120 ab[3].
6. Ge 111 ab or Ge 11 d.
7. Ge 112 or Ge 125.
8. Elective courses in Ge or cross-listed with Ge to bring the total option units up to 210.

[1] *No class may be used to simultaneously satisfy more than one of these requirements.*
[2] *For example, E 11 or En/Wr 84.*
[3] *If Ge 120b is not offered, a suitable 3-5 week field camp may be substituted.*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 & 3	Sophomore mathematics	9	9	-
Ph 2 a & c	Sophomore physics	9	-	9
Ge 11 abc	Intro. To Earth and Planetary Sci.	9	9	9
Ge 106	Intro. to Structural Geology	-	9	-
Ge 120a	Field Geology Intro.1	-	-	6
	HSS electives	9	9	9
		36	36	33
Summer				
Ge 120 b	Field Geology Camp	-	-	18
Third Year				
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
Ge 112	Sedimentology and Stratigraphy	12	-	-
Ge 114 ab	Mineralogy	12	-	-
Ge 115 a	Petrology and Petrography	-	9	-
Ge 111 ab	Applied Geophysics	-	6	9
	HSS electives	9	9	9
		33	36	30

Fourth Year

	Geology electives	9	9	9
Ge 115 b	Petrology and Petrography	-	9	-
	HSS electives	9	9	9
	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
		18	27	24

Geobiology Option Requirements

1. Ge 11 abc, Ge/Ay 11 c, Ge 109, and a science writing course.[1]
2. Ma 2 and one choice from: Ma 3, Bi/CNS/NB 195, Ge/ESE 118 or Ge/Ay 117.
3. Ph 2 a or Ph 12 a plus an additional quarter of sophomore-level physics (Ph2 b, 2 c, 12 b, or 12 c).
4. Ch 41 abc and Bi/Ch 110.
5. Bi 8–10, 117, 122.
6. Two of ESE/Bi 166, ESE/ Bi 168, or Ge/ESE 170.
7. Ge 112.
8. 9 units of geobiology electives from the following list: Bi 123, Bi 180, Ch 4 a, Ch 15, Ge 120 ab, Ch 7, Ch 8, Ge/ESE 143, or Ge 124 ab.
9. 27 units of geobiology electives in geology, biology, chemistry, and/or environmental engineering to be chosen in consultation with adviser, most likely from the list on 8 (above) or from the following list: Ge 11 d, 40, 41 abc, 106, 114, 115 ab, 116, 120 ab, 121 ab, 124 ab, 140 ab, Ge/ESE 149, Ge/Bi 244, 246, BMB/Bi/Ch 170, Bi 22, 24, 90 abc, Bi/Ge 105, Bi/Ch 111, 113, Bi 115, 123, Bi/CNS 150, Bi 152, Bi/CNS 158, Bi 180, 182, 188, 190, 204, Bi/CNS 216, ESE/Bi 168, ESE/Ch 175, 176, ESE 101–103, ESE/Ge/Ch 171, 172, Ch 4 ab, 5 ab, 7, 14, 15, 21 abc, 24, 25, 102, 112, 145, 146, 154 ab, 212.

[1]*For example, Bi 24, E 11, or En/Wr 84*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 & other	Sophomore mathematics	9	9	-
Ph 2 a & c	Sophomore physics	9	-	9
Ge 11 ab, Ge/Ay ll c	Intro. to Earth and Planetary Sci.	9	9	9
	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Cell Biology Laboratory	-	-	6
	HSS electives	9	9	9
		36	36	48

Third Year				
ESE/Bi 166	Microbial Physiology	9	-	-
Ch 41 abc	Organic Chemistry	9	9	9
Ge/ESE 170	Microbial Ecology	-	-	9
	HSS electives	9	9	9
	Geobiology electives	9	9	9
		36	27	36
Fourth Year				
Bi/Ch 110	Intro. to Biochemistry	12	-	-
Bi 117	Developmental Biology	-	9	-
Bi 122	Genetics	9	-	-
Ge 112	Sedimentology and Stratigraphy	12	-	-
	HSS electives	9	9	9
	Geobiology electives	-	9	18
		42	27	27

Geochemistry Option Requirements[1]

1. Ge 11 ab, Ge/Ay 11 c or Ge 11 d, Ge 109, and a science writing course.[2]
2. Ma 2 and one choice from: Ma 3, Ge/ESE 118, Ge/Ay 117, Ph 2c, or Ch 21c.
3. Ph 2 a or Ph 12 a plus an additional quarter of sophomore-level physics (Ph 2 b, Ph 2 c, Ph 12 b, or Ph 12 c).
4. Either ACM 95 ab or the combination of a full-year chemistry sequence (Ch 21 abc or Ch 41 abc) plus Ge/ESE 118.
5. Three courses from the list below:
   Ge 114 ab (counts as one course), Ge 116, Ge 140 a, Ge 140 b, Ch 41 a, Ch 21 a, ESE/Ge/Ch 171, Ge/ESE 149.
6. A total of 105 units from this and item 5 that include at least four courses in the Ge-option:
   Ch electives: Ch 4 a, b, Ch 6a, b, Ch 8, Ch/ChE 9, Ch 14, Ch 15, Ch 21 bc, Ch 41 bc, Ch 102.
   ChE electives: ChE 63 a, b.
   ESE electives: Ge/ESE 143, ESE 103, Ge/ESE 154, ESE/Ge/Ch 172, ESE/Ch 175, ESE/Ch 176.
   Ge electives: Ge 40, Ge 106, Ge 112, Ge 115 a, b, c, Ge 120 a, b, Ge/Ch 127, Ge/Ch 128, Ge/Ay 132, Ge 191, Ge 212, Ge 214, Ge 215, Ge 232.
   APh electives: APh 17 a, b, c.
   MS electives: MS 105, MS 125, MS 131, MS 133, MS/ME 161

[1] No class may be used to simultaneously satisfy more than one of these requirements.
[2] For example, E 11, or En/Wr 84.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
	Scientific Writing	-	-	3

Ge 109	Oral Presentation	-	-	3
	Geochemistry core or electives	9	9	9
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 & other	Sophomore Mathematics	9	9	-
	HSS electives	9	9	9
		45	45	33
Third Year				
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	HSS electives	9	9	9
	Geochemistry core or electives	18	18	18
		27	39	39
Fourth Year				
	HSS electives	9	9	9
	Geochemistry electives	9	9	9
		18	18	18

Geophysics Option Requirements

1. Ge 11 a, Ge 11 b, or Ge 11/Ay c, Ge 109, and a science writing course.[1]
2. Ge 111 ab, Ge 11 d
3. Ph 2 a, Ph 12 a, Ph 2b or 12b, and one of the following: Ph 2c, Ph 12c, ME 11a, Aph 17a, Ch 21c, Ch 25.
4. Ma 2
5. One of Ma 3, Ge/Ay 117, Ge/ESE 118
6. ACM 95 ab
7. 36 units of advanced science courses selected in consultation with adviser and approved by the option representative. Appropriate choices include (but are not limited to): up to 18 units of Me 11and 12, ME 65, 66, AM 125 abc, Ae/Ge/ME 160, Ph 106 abc, MS 115, MS 133, MS/ME/MedE 116.
8. 36 units of geophysics electives (selected in consultation with adviser and approved by the option representative). Appropriate choices include (but are not limited to): up to 9 units of Ge 40 and Ge 41abc, Ge 161–168, Ge 261, Ge 263, ME/Ge/Ae 266ab.

[1] *For example, E 11, or En/Wr 84.*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sciences	9	9	9
	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2	Sophomore Mathematics	9	-	-
Ma 3		-	-	-
	HSS electives	9	9	9
		36	36	33

Third Year				
ACM 95 ab	Intro. to Methods of Applied Math.	-	12	12
	Advanced Science Electives	9	9	9
	HSS electives	9	9	9
Ge 111 ab	Applied Geophysics Seminar	-	6	9
Ge 11 d	Geophysics	-	9	-
		18	45	39
Fourth Year				
	Geophysics electives	18	18	9
	HSS electives	9	9	9
		27	27	18

Planetary Science Option Requirements

1. Ma 2, 3, Ge/Ay 117 or Ge/ESE 118 may substitute for Ma 3.
2. Ph2 a or 12 a, Ph 2 b or 12 b, and one of the following: Ph 2 c, Ph 12 c, APh 17 a, Ch 21 c, Ch 25, ME 11 a.
3. Ge 11 ab, Ge/Ay 11 c, Ge 109, and a science writing course.[1]
4. ACM 95 ab.
5. 45 units of advanced science courses selected in consultation with adviser and planetary science option representatives. Appropriate choices include (but are not limited to): Ae/APh/CE/ME 101 abc, Ae/Ge/ME 160 ab, Ch 21 abc, Ph 101, 106 abc, 125 abc, Ge/ESE 118, ME 12 abc, APh 17 abc, Ay 20, 21, 101, 102, ChE 63 ab, Ch 6 ab, CS 1-3, Ma 112 ab, ME 11 abc, 65, 66, AM 125 abc.
6. 63 units selected from Ge 11 d, Ge 40, 41, 102, Ge/Ay 117, Ge/Ch 128, Ge 131, Ge/Ay 132, Ge/Ay 133, ESE 101-103, Ge/ESE 150, Ge 151, Ge/EE/ESE 157 c, ESE 130, Ge/ESE 139.

[1] *For example, E 11, or En/Wr 84.*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2, 3	Sophomore Mathematics	9	9	-
	HSS electives	9	9	9
		36	36	33
Third Year				
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
HSS electives	9	9	9	
	Advanced science	9	9	9
	Planetary science	9	9	9
		18	39	30

Fourth Year

HSS electives	9	9	9
Planetary science	9	9	9
Additional science and engineering	9	9	9
	27	27	27

GPS Minor Requirements

The GPS minor is intended for non-GPS undergraduates to supplement a major degree with knowledge of earth and planetary science. Students completing the GPS minor will have the phrase "minor in Geological and Planetary Sciences" added to their transcript. Any student interested in a minor in GPS is urged to contact any option representative in the division.

1. Ge 11 a and Ge 11 b.
2. One of Ge/Ay 11 c or Ge 11 d.
3. 27 units of 100-level or higher GPS courses, excluding Ge 108 and Ge 109.

History Option and Minor

The history option allows students to study past societies and their development in more depth than can be done within the limits of the Institute humanities requirements. With the guidance of a faculty member in history, students taking the option explore the range of human experience, in the realms of politics, culture, religion, and economics, that lies outside the realm of science and technology. They also learn the critical reading and thinking skills, and the facility in writing, that are central to the historical enterprise. The history option thus provides students with an important supplement to the scientific training and technical skills they acquire in other courses and options. In addition, it offers excellent preparation for careers in business, administration, law, journalism, or public affairs, as well as a solid foundation for graduate work in history.

History majors must take at least 99 units of history courses (including freshman humanities) during their four years as undergraduates. Of these, 27 must be in the senior tutorial (H 99 abc). All courses to be counted toward the history option must be taken for grades except for a freshman humanities course in history when taken in the first two quarters of the freshman year.

Each history major will choose an area of concentration in consultation with his or her adviser and the history option representative. These areas might include, but are not restricted to, fields such as ancient history, medieval Europe, early-modern Europe, modern Europe, Russian history, American history pre-1865, American history post-1865, early-modern history of science, modern history of science, or economic history. He or she must take 63 units of courses in this area; 27 of these units must be in the senior tutorial H 99 abc. The senior tutorial will culminate in a research paper.

Each student must take the remaining 36 units of history required by the option in areas other than the area of concentration, again defined in consultation with his or her adviser and the history option representative. These areas may include not only fields within the discipline of history proper, but also useful cognate fields such as economics, political science, anthropology, law, English, or a foreign language.

A student considering the history option when he or she comes to Caltech will be well advised to take one course from Hum/H 1, 2, 3, or 4. In the sophomore year, the student should take upper-level history courses, but this is also a good time to pursue the study of English or philosophy, to begin or continue a foreign language, and to do introductory work in the social sciences. A student will normally make a commitment to an area of concentration early in the junior year. At the beginning of the senior year, a history major will enroll in H 99 abc with a faculty member in his or her area of concentration. The first term of this course will be devoted to preparation, the second to research, and the third to the writing of a substantial research paper.

Option Requirements

1. H 99 abc.
2. 72 additional units of history courses numbered 99 or above. Up to nine units of Hum/H 1, 2, 3, or 4 and/or up to nine units of H 98 may be substituted for up to 18 of these units.
3. 63 of the total history units, including H 99 abc, must be in an area of concentration, as defined in consultation with the student's adviser and the history option representative.
4. 36 of the total history units must be in an area or areas other than the area of concentration, as defined in consultation with the student's adviser and the history option representative. H 99 abc may not be used to fulfill this requirement.
5. 54 additional units of science, mathematics, and engineering courses. This requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by menu courses.
6. Three units of oral communication. En 84 satisfies this requirement, as do oral communication courses offered by other options.
7. Passing grades must be earned in a total of 486 units, including the courses listed above.

Courses used to complete the history option under categories 1, 2, or 3 above may not be used to satisfy the requirements of another option or minor.

History Minor Requirements

The history minor is designed for students who want to pursue concentrated study in history without the extensive course work and the senior thesis required by the history option.

History minors must take 72 units of history courses. These units may include one freshman humanities course; they may also include one directed reading course (H 98). All courses to be counted toward the history minor must be taken for grades except for a freshman humanities course in history when taken in the first two quarters of the freshman year. Students wishing to do a minor in history must declare a minor with the history option representative. Students completing the history minor requirements will have the phrase "minor in history" added to their transcripts.

1. 72 units of history courses numbered 99 or above.
2. Nine units of Hum/H 1, 2, 3, or 4 may be substituted for any nine of the 72 units required for the minor.
3. Nine units of H 98 may be substituted for any nine of the 72 units required for the minor.

Students cannot use history minor requirements to satisfy a different option or minor.

History and Philosophy of Science Option and Minor

Students in History and Philosophy of Science (HPS) explore the historical evolution of the sciences and the philosophical perspectives that inform them, as well as the dynamics between science, technology, and other human endeavors. HPS may be pursued as an undergraduate option or minor, or on a course-by-course basis.

Historical research in HPS includes the origins of experimental practice, the social and institutional contexts of science, the origins and applications of quantitative methods, specific developments since antiquity in biology, chemistry, geography and cartography, medicine, and physics, as well as biographical and comparative studies in these fields. Philosophical research in the program deals with issues in causation, explanation, scientific inference, the foundations of probability and decision theory, philosophy of mind, psychology, and neuroscience.

HPS offers students with broad education in the historical and philosophical issues arising in connection with science and technology. Students take courses addressing fundamental questions about scientific concepts and practice, such as the following: To what extent was the scientific revolution revolutionary? What is a scientific explanation and how do scientists go about constructing and justifying one? How have conceptions of scientific experimentation changed over time? How and why did modern physics (or chemistry or biology) emerge in the form that it did? How should the theory of evolution inform our conception of the modern mind and brain? What role can the neurosciences be expected to play in solving the 'mind-body' problem? The option thus aims to give students a broad basic understanding of the ways in which science is practiced, and the ways in which that practice has changed over time. It is designed to complement the regular curriculum at Caltech, offering students the opportunity to enlarge upon, and to contextualize, the strong technical skills they acquire in other courses and options.

The HPS option provides excellent preparation for students going into law, business, medicine, and public affairs, as well as solid preparation for graduate work in history and/or philosophy of science. In addition, and because of its emphasis on essay writing and the formulation of complex philosophical and historical arguments, it aids budding scientists and engineers in developing the writing and communication skills that are increasingly vital today.

Option Requirements

1. Hum/H/HPS 10; HPS 102 ab; HPS/Pl 120; and HPS 103 (one quarter). (HPS 102 b fulfills the Institute science writing requirement.)
2. One advanced course in the history of science, chosen from HPS/H offerings with a course number of 98 or higher; one advanced course in philosophy of science, chosen from HPS/Pl offerings with a course number of 98 or higher; and any four courses in HPS. (No more than 9 units of HPS 98 may be counted towards the HPS major.)
3. 45 units of courses in science, mathematics, and engineering. This requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by a course with a number less than 10.
4. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Courses used to complete the history and philosophy of science option under categories 1, 2, or 3 above may not be used to satisfy the requirements of another option or minor.

We recommend that students intending to follow the HPS option take Hum/HPS/H 10 "Introduction to History of Science" as one of their Freshman humanities courses. Students making the decision to take this option in their sophomore year should take Hum/HPS/H 10 and HPS/Pl 120 "Introduction to Philosophy of Science" as early as possible in that year. Students may also enter the option in their junior year if they can complete the option's requirements in time for graduation. Please also note the following:

1. *Not all required courses are offered each term; students should consult the current catalog to determine which terms required courses are being offered, and should construct their course plan for the year accordingly.*
2. *We encourage students to choose their advanced social science electives from among courses that will enlarge their perspective on topics related to HPS (for example, Ec 118, Ec/SS 128, Ec/SS 129, Ec/SS 130, PSY 101, PSY 115, PSY 125, PSY 130, PS 120, PS 121, PS 122, An 22, An 123).*
3. *HPS 102ab, the Senior Research Seminar, may be taken in any two consecutive terms in the Senior year. Students should coordinate with their HPS advisor in determining their course schedule.*

Typical Course Schedule

First Year

It is recommended that students intending to follow the HPS option take Hum/H/HPS 10 as one of their freshman humanities courses. Students making the decision to take this option in their sophomore year should take Hum/H/HPS 10 and HPS/Pl 120 as early as possible in that year.

		Units per term 1st	2nd	3rd
Second Year				
HPS 10[1]	Introduction to History of Science	9	-	-
HPS/Pl 120[1]	Introduction to Philosophy of Science	-	9	-
	Advanced HPS/history	-	-	9
HPS 103	Public Lecture Series	1	1	1
	Menu course	-	-	9
Ec 11	Introductory Social Science			
or PS 12		9	-	-
	Other electives	27	36	27
		46	46	46
Third Year				
HPS 103	Public Lecture Series	1	1	1
	Advanced HPS/history	-	9	9
	Advanced HPS/philosophy	9	9	9
	Science, math, engineering	9	9	9
	Advanced social science[2]	9	-	-
	Other electives	18	18	18
		46	46	46
Fourth Year				
HPS 103	Public Lecture Series	1	1	1
HPS 102 ab[3]	Senior Research Seminar	-	12	12
	Advanced social science[2]	9	-	-
	Science, math, engineering	9	9	9
	Other electives	27	18	18
		46	40	40

Note: *Not all required courses are offered each term; students should consult the current catalog to determine which terms required courses are being offered, and should construct their course plan for the year accordingly.*

[1] *If not taken in first year; otherwise one additional HPS or elective.*

[2] *It is recommended that students choose their advanced social science electives from among courses that will enlarge their perspective on topics related to HPS (e.g., Ec/SS 129, Ec/SS 130, Psy 101, Psy 125, Psy/CNS 130, PS 120, PS 121, PS 122, An 22).*

[3] *HPS 102 ab may be taken in any two consecutive terms in the senior year. Students should coordinate with their HPS adviser to determine their course schedule.*

History and Philosophy of Science Minor Requirements

The minor in HPS is designed for students who want to pursue concentrated study in the field without the extensive course work and the senior thesis required by the HPS option.

HPS minors must complete 72 units of HPS courses. These may include Hum/H/HPS 10 and up to 9 units of advanced reading in HPS (HPS 98). Freshman Humanities courses other than Hum/H/

HPS 10 may not be counted towards an HPS minor. Students wishing to do a minor in HPS must declare a minor with the HPS option representative. Those completing the HPS minor requirements will have the phrase 'minor in History and Philosophy of Science' added to their transcripts.

1. 72 units of HPS courses numbered 99 or above.
2. 9 units of HPS 98 may be substituted for any 9 of the 72 unit required for the minor.
3. 9 units of Hum/H/HPS 10 may be substituted for any 9 of the 72 units required for the minor.

Students cannot use HPS minor requirements to satisfy a different option or minor.

Interdisciplinary Studies Program

The Interdisciplinary Studies Program (ISP) is an undergraduate option that allows the student to create his or her own scholastic requirements, under faculty supervision, and to pursue positive educational goals that cannot be achieved in any of the other available options. A student's program may include regular Caltech courses, research courses, courses at other schools, and interdisciplinary study courses (item 5, next page). In scope and depth, the program must be comparable to a normal undergraduate program, but it need not include all of the specific courses or groups of courses listed in the formulated Institute option requirements for undergraduates.

The Curriculum Committee, a standing committee of the faculty, has overall responsibility for the program. In addition, each student has his or her own committee of at least two advisers, two of whom must be professorial faculty. Application material may be obtained at the Dean of Undergraduate Students office or website.

Administrative Procedures and Guidelines

1. An interested student must recruit at least two professorial faculty members representing at least two different degree-granting options to serve as the ISP faculty committee. Each member of the faculty committee must provide a letter that includes:
    a. Faculty name and department/division, and the discipline they "represent" within the proposed ISP.
    b. Faculty's assessment of the student's ISP proposal, including the proposed degree title, as it relates to that faculty's discipline.
    c. Faculty assessment of whether the student could choose an existing degree-granting option with some acceptable accommodations, rather than create an ISP. That is, does this ISP enable something that could not be accomplished in a single option or major/minor combination.
2. Send the ISP proposal (cover sheet, proposed curriculum, and the aforementioned letters from professorial faculty advisors to the Dean of Undergraduate Students for review and approval.

3. The Dean of Undergraduate Students sends the ISP petition to the Curriculum Committee for review and final approval. This contract includes the agreed-upon content of the student's program and the methods for ascertaining satisfactory progress for those parts of the student's program that are not standard Institute courses. This contract may of course be amended, but any amendments must be approved by the committee of two and the Curriculum Committee. Copies of each student's contract and of all amendments thereto, along with all ISP records for each student and his or her transcript, are kept in the permanent files of the Registrar's Office. Passing grades must be earned in a total of 486 units.
4. The progress of each student in the ISP is monitored each quarter by the registrar, and any deviations from the terms of the contract are reported to the chair of the Curriculum Committee. Standards for acceptable progress and for satisfactory completion of the terms of the contract are the responsibility of the Curriculum Committee. When the Committee is satisfied that the terms of the contract have been fulfilled by the student, it recommends the student to the faculty for graduation.
5. A plan of study may include special ISP courses to accommodate individual programs of study or special research that falls outside ordinary course offerings. In order that credit be received for an ISP course, a written course contract specifying the work to be accomplished, time schedule for progress reports and completed work, units of credit, and form of grading must be agreed upon by the instructor, the student, and the committee of two, and submitted to the registrar prior to initiating the work in the course. ISP courses are recorded on the student's transcript in the same manner as are other Caltech courses.
6. ISPs are intended for multiyear programs. Accordingly, the Curriculum Committee urges students contemplating an ISP to submit their petition during their second year and will not normally consider such petitions any later than the first term of the student's third year.

Mathematics Option

The four-year undergraduate program in mathematics leads to the degree of Bachelor of Science. The purpose of the undergraduate option is to give students an understanding of the broad outlines of modern mathematics, to stimulate their interest in research, and to prepare them for later work, either in pure mathematics or allied sciences. Unless students have done very well in mathematics courses in their freshman and sophomore years, they should not contemplate specializing in mathematics.

Since the more interesting academic and industrial positions open to mathematicians require training beyond a bachelor's degree, students who intend to make mathematics their profession must normally plan to continue with graduate study. Some students use their background in mathematics as an entry to other fields, such as physics, computer science, statistics, economics, business, finance, medicine, or law.

The schedule of courses in the undergraduate mathematics option is flexible. It enables students to adapt their programs to their needs and mathematical interests and gives them the opportunity to become familiar with creative mathematics early in their careers. In particular, students are encouraged to consider courses in areas such as applied and computational mathematics, physics, finance, economics, control and dynamical systems, computer science, electrical engineering, and computation and neural systems.

Freshman considering majoring in mathematics should be aware that the department strongly reccomends taking the analytical track of Ma 1bc. During each term of their junior and senior years, students normally take 18 units of courses in mathematics or applied and computational mathematics, including the required courses Ma 108 abc and 109 abc. Any course listed under applied and computational mathematics is regarded as an elective in mathematics and not as an elective in science, engineering, or humanities. Those who have not taken Ma 5 as sophomores must do so as juniors. Overloads in course work are strongly discouraged; students are advised instead to deepen and supplement their course work by independent reading.

A student whose grade-point average is less than 1.9 at the end of the academic year in the subjects under mathematics and applied and computational mathematics may, at the discretion of the department, be refused permission to continue work in the mathematics option.

Option Requirements

1. Ma 2.
2. Ma 3 or Ma 144a.
3. Either Ph 2bc or Ph 12abc (the departmental recommendation is the Ph 12abc sequence).
4. Ma 5 abc, Ma 10, Ma 108 abc, Ma 109 abc.
5. Ma/CS 6 a or Ma 121 a.
6. Ma/CS 6 c or Ma 116 a or Ma/CS 117 a.
7. 45 additional units in Ma numbered 110 or above or ACM numbered 95 or above. Courses in other options with high mathematical content may be used to fulfill this requirement with the approval of the executive officer for mathematics. Of these 45 units, at most 18 can be in ACM or other courses outside Ma. Math courses taken elsewhere and allowed (such as in a study abroad program) are included in this 18 units outside of Caltech Ma courses.
8. Math majors must take two quarters (18 units) of a single course, chosen from the Ma course listings with numbers between 110 and 190, inclusive. (In years where one of these courses is given as a one-term course only, it cannot be used to

satisfy this requirement.) These two quarters may be used to meet requirements 2, 5, 6 or 7.

9. Unlike courses satisfying requirements 7 and 8, which may be taken pass/fail, none of the courses satisfying requirements 1–6 may be taken on a pass/fail basis.
10. Passing grades must be earned in a total of 486 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2, 3	Sophomore Mathematics	9	9	-
Ph 2 bc	Sophomore Physics	-	9	9
Ma 5 abc	Introduction to Abstract Algebra	9	9	9
	HSS electives	9	9	9
	Electives[1]	18	9	18
		45	45	45
Third Year				
Ma 10	Oral Presentation	3	-	-
Ma 108 abc	Classical Analysis	9	9	9
Ma/CS 6 ac	Introduction to Discrete Mathematics	9	-	9
	HSS electives	9	9	9
	Electives[1]	18	27	18
		48	45	45
Fourth Year				
Ma 109 abc	Introduction to Geometry and Topology	9	9	9
	HSS electives	9	9	9
	Electives[1]	27	27	27
		45	45	45

[1] *Includes menu course (second year, if not taken in freshman year). Also must include courses to meet option requirements 4, 5.*

Mechanical Engineering Option

The objective of the undergraduate program in Mechanical Engineering at Caltech is to produce graduates who will attain careers and higher education that ultimately lead to leadership roles in academia, industry and government in areas of rapidly advancing interdisciplinary technology related to fluid, solid, thermal and mechanical systems.

The program prepares students for graduate school and professional practice and inspires them to undertake careers that provide an opportunity to address the pressing technological needs of society. Specifically, the program builds on Caltech's core curriculum to combine individual depth of experience and competence in a particular chosen mechanical engineering specialty with a strong background in the basic and engineering sciences. It maintains a balance between classroom lectures and laboratory and design experience, and emphasizes the problem-formulation and solving skills that are essential to any engineering discipline. The program also strives to develop in each student self-reliance, creativity, leadership, professional ethics, and the capacity for continuing professional and intellectual growth. For interested students, there are opportunities to conduct research with a faculty member.

The outcome of the undergraduate program is to prepare the student to build on a fundamental education in physics, mathematics, chemistry and biology and to apply those principles to the solution of open ended engineering problems; to design, analyze, measure, and evaluate fluid, thermal and mechanical systems; to work effectively as part of a team; to communicate effectively; to apply ethical considerations; and to understand the broader impacts of engineering developments, including societal, cultural and environmental concerns.

Mechanical engineering is the branch of engineering that is generally concerned with understanding forces and motion, and their application to solving problems of interest to society. The field includes aspects of thermodynamics, fluid and solid mechanics, mechanisms, materials, and energy conversion and transfer, and involves the application of physics, mathematics, chemistry, and increasingly, biology and computer science. Importantly, the field also emphasizes the process of formulation, design, optimization, manufacture, and control of new systems and devices.

Technical developments in the last decade have established the importance of interdisciplinary engineering and science, and as a result, new technical disciplines within mechanical engineering have emerged. These new areas build on an understanding of the fundamental behavior of physical systems; however, the focus of this work is at the interfaces between traditional disciplines. Examples of the new disciplines include: micro- and nano-mechanical systems, simulation and synthesis, integrated complex distributed systems, and biological engineering.

Mechanical engineers can be found in many fields including automotive, aerospace, materials processing and development, power production, consumer products, robotics and automation, semiconductor processing, and instrumentation. Mechanical engineering can also be the starting point for careers in bioengineering, environmental and aeronautical engineering, finance, and business management.

The mechanical engineering option is accredited by the Engineering Accreditation Commission of ABET, 111 Market Place, Suite 1050, Baltimore, MD 21202-4012, (410) 347-7700.

At the end of the first year, students who elect the mechanical engineering option are assigned advisers as close to their expressed field of interest as possible, and together they develop programs of study for the next three years.

A student whose interests relate to mechanical engineering, but who wishes to pursue a broader course of study than that allowed by the requirements below, may elect the engineering and applied science option.

Attention is called to the fact that any student whose grade-point average is less than 1.9 at the end of the academic year in the required courses listed below may be refused permission to continue work in this option.

Option Requirements

1. Technical communication: E10 and E11
2. Mathematics: Ma 2, ACM 95 a, ACM 95 b, and 18 units selected from Ma 3, 4, 5abc, 6abc, 7, 91a, or any Math or ACM courses numbered 100 and above.
3. Physics: 18 units selected from Ph 2abc.
4. Computing: 9 units selected from ACM 11, CS1, CS2, CS11, or EE/CS 51.
5. ME Core: ME11abc, ME12abc, ME13, ME14, and ME 50ab.
6. Capstone design: ME72ab or E/ME 105ab or ME90abc or CS/EE/ME75abc*.
7. 45 units of advanced mechanical engineering electives selected from ME courses with numbers greater than 100, excluding courses listed above, and/or advanced courses in related disciplines**.
8. Courses satisfying requirements 1 through 7 must be taken for grades, unless they are only offered pass/fail.

** Students electing CS/EE/ME 75abc must complete at least 18 units distributed amongst all three quarters*

*** These courses are selected in consultation with the student's faculty advisor and typically taken in the third and fourth years. The course selections must be approved in advance by the advisor, but can be later modified, again with the approval of the advisor. Specialization tracks include micro- and nano-mechanical systems, systems, kinematics, dynamics, fluid mechanics, solid mechanics, control systems, design, thermal systems, energy, combustion, and biological engineering. Please consult the Mechanical and Civil Engineering website and/or the advisor for further information.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2	Differential Equations	9	-	-
	Computing Elective	9	-	-
ME 11 abc	Thermal Science	9	9	9
ME 12 abc	Mechanics	9	9	9
ME 13	Introduction to Mechanical Prototyping	-	4	-
ME 14	Design and Fabrication	-	-	9
		36	22	27
Third Year				
	Math Electives	9	-	-
	Physics Electives	9	-	9
ACM 95 ab	Intro. Meth. Applied Math.	-	12	12
ME 50 ab	Exp. and Modeling in ME	-	9	9

	Capstone Design	9	9	-
E 10	Technical Seminar Presentation	-	-	3
E 11	Written Technical Communication	3	-	-
		30	30	33
Fourth Year				
	Math Electives	-	9	-
	Advanced ME electives	18	18	9
		18	27	9

Philosophy Option and Minor

The philosophy option provides students with a broad education in philosophy. The courses in the philosophy option concentrate in four major areas: philosophy of science; philosophy of mind, brain, and behavior; history of philosophy; and moral and political philosophy. The option is designed to complement the scientific curriculum at Caltech, to provide students with new perspectives on the material they learn in their science courses, and to enable them to bring their technical skills and scientific learning to traditional problems in philosophy. In addition, the philosophy option focuses on the development of rigor in argument, as well as clarity in written and oral communication.The philosophy curriculum will provide interested students with a solid foundation for graduate work in philosophy. In addition, the analytical and communication skills learned in the philosophy option provide an excellent foundation for careers in law, business, medicine, and scientific research.

Philosophy majors must take at least 99 units of philosophy courses during their four years as undergraduates. These must include 18 units of Pl 90 ab, to be taken in any two consecutive terms in the senior year. The 99 units may include nine units of either Hum/Pl 8 or Hum/Pl 9, nine units of Pl 98, and up to 18 units of study in related disciplines.

Depending on their interests, philosophy majors may be required by the option representative or their advisers to take up to 18 units in one or more related areas. For example, students writing on political philosophy or philosophy of neuroscience will be expected to have the appropriate political science or neuroscience background. Students whose primary interest lies in the philosophy of science—particularly in the philosophy of particular sciences such as physics or biology—will have their intellectual interests best served by taking classes in both the history and philosophy of science. Such students are encouraged to pursue the HPS option; or, if they choose the philosophy option, they may be required to take some history of science courses toward their 99-unit requirement.

Students considering the philosophy option will be well advised to take either Hum/Pl 8 or Hum/Pl 9 as one of their freshman humanities courses. From the sophomore year onward, they should plan on taking one philosophy course per term, culminating in two terms of Pl 90 ab in the senior year. Students in Pl 90 ab work with a faculty adviser to write a 10,000–12,000 word paper on a topic of mutual interest. Senior theses are expected to be of a high standard and to form the basis of students' applications to graduate study in philosophy, should they so desire. With the exception of courses taken during the first two semesters of freshman year, all courses to be counted toward the philosophy option must be taken for grades unless special permission is granted by the option representative.

Option Requirements

1. Pl 90 ab.
2. 63 units of advanced philosophy courses, numbered 99 or above. (Up to nine units of Hum/Pl 8 or Hum/Pl 9 and/or up to nine units of Pl 98 may be substituted for up to 18 of these advanced units.)
3. 18 units of advanced philosophy courses numbered 99 or above, or advanced non-philosophy courses that are closely related to the student's area(s) of philosophical interest. (Students wishing to count non-philosophy courses toward their option requirements must obtain prior approval from the philosophy option representative or their adviser. Students will normally not be permitted to satisfy this requirement with core courses.)
4. 54 units of science, mathematics, and engineering courses in addition to the core. This requirement cannot be satisfied by core or menu courses, or by courses listed as satisfying the introductory laboratory requirement. Students are strongly encouraged to choose their additional courses in areas that complement their philosophy studies.
5. Passing grades must be earned in a total of 486 units, including the courses listed above.

Courses used to complete the philosophy option under categories 1, 2, or 3 above may not be used to satisfy the requirements of another option or minor.

Philosophy Minor Requirements

The minor in philosophy is designed for students who want to pursue concentrated study in philosophy without the extensive course work and the senior thesis required by the philosophy option.

Philosophy minors must complete 72 units of philosophy courses. These units may include nine units of Hum/Pl 8 or Hum/Pl 9 and/or nine units of reading in philosophy (Pl 98). Students wishing to do a minor in philosophy must declare a minor with the philosophy option representative. Students completing the philosophy minor requirements will have the phrase "minor in philosophy" added to their transcripts. With the exception of courses taken during the first two semesters of freshman year, all courses to be counted toward the philosophy minor must be taken for grades unless special permission is granted by the option representative.

1. 72 units of philosophy courses numbered 99 or above.
2. Nine units of Pl 98 may be substituted for any nine units of the 72 required for the minor.

3. Nine units of either Hum/Pl 8 or Hum/Pl 9 (not both) may be substituted for any nine units of the 72 required for the minor.

Courses used to complete the philosophy minor may not be used to satisfy the requirements of another option or minor.

Physics Option

The physics option offers instruction in the fundamentals of modern physics and provides a foundation for graduate study, which is generally necessary for a career in basic research. The physics program also forms an excellent basis for future work in a variety of applied fields.

An intensive version of the sophomore physics course (waves, quantum mechanics, and statistical mechanics) is offered for those planning further study in physics, and the required junior-level courses give a thorough treatment of fundamental principles. Elective courses ta en during the junior and senior years allow students to explore their particular interests. Some electives offer broad surveys, while others concentrate on particular fields of current research. A choice of laboratory courses is offered at several levels.

Students are encouraged to become active participants in research on campus, both during the summer and during the school year. Academic credit for physics work done outside of the classroom can be awarded in a variety of ways.

Students must maintain a grade-point average of 1.9 or better each year in the subjects listed under this division to remain in the physics option.

Option Requirements

The first five requirements should be completed by the end of the second year. In planxning a program, note that Ph 6 and Ph 7 are each offered only once per year, in the second and third terms, respectively.

1. Ph 3.[1]
2. Ma 2 and Ma 3.
3. Ph 12 abc.
4. Ph 6.
5. Ph 7.
6. 27 units of Ph 78, or 18 units of Ph 77, or 9 units of Ph 77 and 9 units from APh 77 or Ay 105.
7. Ph 70.[2]
8. Ph 106 abc.
9. Ph 125 abc.
10. Ph 127 a.
11. Ph 21 or Ay 190.

[1] *Other laboratory courses may be substituted for the Ph3 requirement, including Ph 5, Ph 8bc, or APh 9a.*

[2] *Other communication courses (e.g., AY 30 and 31 or MA 10 and 11 may be substituted for Ph 70.*

Required Electives

1. 72 units of Advanced Physics Electives, in addition to the above, including any of the following: any Ph, APh, or Ay, course numbered 100 or above, or any of Ph 5, Ph 22, Ph 78, Ph 79, ACM 95, ACM 101, Ma 5, Ma 108, or up to 10 units of Ay 20–21. Nine units toward the 72-unit requirement will be given for taking three terms of Ph 77. Students are encouraged to take ACM 95 as part of this requirement. The pass/fail option cannot be exercised on any courses used for this requirement, with the exception of ACM 95 and courses that do not offer grades. No more than 36 units of Ph courses numbered 200 or above taken on a pass/fail basis may apply toward this requirement. No more than 18 units of Ph 171–173 may apply toward this requirement without permission from the Physics Executive Officer. Additionally, Ph 171-173 may only apply towards this requirement if taken in increments of six units or more. Students may also petition the Executive Officer to request that other courses with suitable physics content apply toward this requirement, as part of a specified overall list of Advanced Physics Electives.
2. Nine units of science or engineering electives outside of Ph, Ay, APh, Ma, and ACM. These units are in addition to the required Core science electives.
3. Passing grades must be earned in a total of 486 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 12 abc	Waves, Quantum Physics, and Statistical Mechanics	9	9	9
Ma 2, Ma 3	Sophomore Mathematics	9	9	-
	HSS and/or PE electives	18	9	9
	Physics laboratory	-	9	9
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	Computational Physics	9	-	-
	Core Science Elective	-	-	9
		45	48	48
Third Year				
Ph 106 abc	Topics in Classical Physics	9	9	9
Ph 125 ab	Quantum Mechanics	9	9	9
Ph 127 a	Statistical Physics	9	-	-
	HSS and/or PE electives	9	9	9
	Electives	9	18	18
		45	45	45
Fourth Year				
Ph 77 abc	Advanced Physics Laboratory	9	9	-
Ph 70	Oral and Written Communication	-	6	-
	Advanced physics electives	18	18	18

Electives	9	6	18
HSS and/or PE electives	9	9	9
	45	48	45

Political Science Option

The political science option provides students with training in the substance and methods of modern political science, including the analysis of representative democracy, electoral institutions, the allocation of public goods, and regulatory behavior. The option emphasizes formal tools like game theory, social choice theory, and formal political theory along with quantitative methodologies to test those theories. In addition, the option encourages original research. The design of the political science option ensures that students will be well suited to pursue careers in government or the private sector, as well as to pursue graduate work in political science.

Option Requirements

1. PS 12, PS 132, Ec 122.
2. Four political science courses from the list: PS 120, 123, 126, 130, 135, PS/SS 139, PS 141, Law/PS/H 148 ab, PS/Ec 172.
3. PS 99 ab.
4. Ma 3
5. 36 additional units in advanced political science, economics, law, social science, psychology, or history.
6. 36 additional units in advanced social science, science, engineering, or mathematics.
7. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma3	Probability & Statistics	-	9	-
PS 12	Introduction to Political Science	9	-	-
PS 132	Formal Theories in Political Science	-	9	-
Ec 122	Econometrics	-	9	-
	Electives	36	18	45
		45	45	45
Third Year				
	Political science electives[1]	18	18	18
	Electives	27	27	27
		45	45	45
Fourth Year				
PS 99 ab	Research in Political Science	-	9	9
	Political science electives[1]	18	18	18
	Electives	27	18	18
		45	45	45

[1] *See option requirements 2, 5, 6.*

Structural Mechanics Minor

This minor is intended to supplement one of Caltech's undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major, especially for those who wish to join the structural engineering profession after graduation or pursue a graduate degree in structural mechanics or structural engineering. Students completing the structural mechanics minor requirements will have the phrase "minor in structural mechanics" added to their academic transcripts.

Minor Requirements

The student must complete 54 units of classes selected from Ae/AM/CE 102 abc, AM/CE 151 ab, and CE 160 ab, and obtain a grade of B– or higher. Courses taken as part of the structural mechanics minor are counted toward the total 486-unit Institute graduation requirement.

Section Four

Information for Graduate Students

The Institute offers graduate work leading to the degrees of Master of Science and Doctor of Philosophy, and in special cases the degree of Engineer.

The academic work of the Institute is organized into six divisions: Biology and Biological Engineering; Chemistry and Chemical Engineering; Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics and Astronomy.

Graduate work at the Institute is further organized into graduate options, which are supervised by those professors whose interests and research are closely related to the area of the option, within the administrative jurisdiction of one or more of the divisions.

The graduate student working for an advanced degree in one of the graduate options is associated with an informal group of those professors who govern the option, other faculty including research associates and fellows, and other graduate students working for similar degrees.

A faculty member serves as the representative for an option. The option representative provides consultation on academic programs, degree requirements, financial aid, etc., and provides general supervision to graduate students in the option. The Committee on Graduate Studies, which includes the option representatives, elected members of the faculty at large, and graduate students appointed by the Graduate Student Council, exercises supervision over the scholastic requirements established by the faculty for all advanced degrees, provides policy guidance to the dean of graduate studies, and certifies all candidates for graduate degrees to the faculty for their approval. The option representatives for 2014-2015 are as follows:

Aerospace	Prof. B. McKeon
Applied and Computational Mathematics	Prof. T. Hou
Applied Mechanics	Prof. J. Andrade
Applied Physics	Prof. O. Painter
Astrophysics	Prof. L. Hillenbrand
Behavioral and Social Neuroscience	Prof. M. Shum
Biochemistry and Molecular Biophysics	Prof. W. Clemons
Bioengineering	Prof. R. Murray
Biology	Prof. B. Hay
Chemical Engineering	Prof. K. Giapis
Chemistry	Prof. M. Okumura
Civil Engineering	Prof. J. Andrade
Computation and Neural Systems	Prof. T. Siapas
Computer Science	Prof. C. Umans
Computing and Mathematical Sciences	Prof. C. Umans
Control and Dynamical Systems	Prof. R. Murray
Electrical Engineering	Prof. A. Hajimiri

Environmental Science and Engineering	Prof. A. Thompson
Geological and Planetary Sciences	Prof. R. Clayton
Materials Science	Prof. B. Fultz
Mathematics	Prof. T. Graber
Mechanical Engineering	Prof. J. Andrade
Medical Engineering	Prof. A. Emami
Neurobiology	Prof. M. Meister
Physics	Prof. F. Porter
Social Science	Prof. M. Shum

GRADUATE POLICIES AND PROCEDURES

Admission to Graduate Standing

Application

An application for admission can be completed electronically through the Graduate Office website. Admission will be granted only to a limited number of students of superior ability, and application should be made by the posted deadlines. Completed applications are due in the Graduate Office between December 15 and January 15. Please refer to the Graduate Office website for specific deadlines. Some options will review an application received after the deadline, but that applicant may be at a disadvantage in the allocation of financial assistance or in the priority for admission. In general, admission to graduate standing is effective for enrollment only at the beginning of the fall term. The California Institute of Technology encourages applications from members of groups underrepresented in science and engineering, including women. Graduate admissions is covered by Caltech's Nondiscrimination Policy. For more information on this policy, please refer to page 68. Applicants will automatically be considered for financial aid; no additional application is required.

To be admitted to graduate standing, an applicant must in general have received a bachelor's degree representing the completion of an undergraduate course in science or engineering equivalent to one of the options offered by the Institute. He or she must, moreover, have attained such a scholastic record and present such recommendations as to indicate fitness to pursue, with distinction, advanced study and research. Admission sometimes may have to be refused solely on the basis of limited facilities in the option concerned.

Required Tests

The verbal, quantitative, and writing components of the Graduate Record Examination are required by all graduate options, and sub- ject scores are required by some options as part of the application for graduate admission.

International Students

In order to be admitted for graduate study, students from non-English-speaking countries are expected to read, write, and speak English and comprehend the spoken language. Although not required for admission, it is important to demonstrate a strong capability in English prior to admission to Caltech, as it is one of the criteria for admission and financial aid. In addition, to be a candidate for an advanced degree, the student must have clear self-expression in both oral and written English.

Applicants whose first or native language is not English are required to take a test of English proficiency as part of the application procedure. These tests are given at centers throughout the world, on several dates each year. Caltech recognizes scores from the Educational Testing Service (TOEFL), Pearson Test of English Academic (PTE Academic), and from the Cambridge Examinations and the International English Language Testing System (IELTS). Applicants should arrange for the results of these tests to be sent to the Graduate Office prior to the application deadline (institutional code 4034).

The testing schedules for and information on the TOEFL may be obtained online at http://www. toefl.org.

The testing schedules for and information on the IELTS exam may be obtained online at http://www. ielts.org.

It is strongly recommended that students who do not achieve a high score on these tests, or who have little opportunity to com- municate in English, make arrangements for intensive work during the summer preceding their registration. All international students are tested upon arrival at Caltech and, if found to be seriously defi- cient in their ability to communicate in English, must take special courses in English as a Second Language (ESL).

Visiting Student Appointments

A limited number of visiting student appointments are made each year. Visiting student status is restricted to students who hold a bachelor's degree or the equivalent and are registered in, or are on sabbatical from an advanced degree program at another institution and who need to make use of resources available at Caltech. The invitation process requires sponsorship by a Caltech faculty member, and requests should be made directly to the Graduate Office by the faculty host, following the visiting student instructions on the Graduate Office website. The dean of graduate studies may limit the number of visiting students invited by faculty in any given year. Visiting students are subject to the Honor System (see page 35) and are under the purview of the dean of graduate studies. Visiting students are categorized into two main classifications.

Special Students

Special students must enroll as full-time students (36 units), in a research course and/or coursework numbered 100 or higher, which may be transferred to their home institution. Special students will not be considered to be working toward a Caltech degree, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree, nor does registration count toward the minimum residency requirement for an advanced degree. Special students are required to check in with the Registrar's Office upon arrival, and international students must check in with the office of International Student Programs.

Special students are eligible for the same privileges as regularly enrolled graduate students, and will be billed for tuition and fees. For those students who receive a Caltech stipend, tuition remission will be charged to the faculty hosts' supporting grant to cover the tuition and fees assessment. Special students who do not receive a Caltech stipend will be billed the minimum tuition and fees rate. (For current rates, see the expense summary on page 301.)

Special Student appointments are allowed for one year, renewable each year up to a maximum of three years.

Visiting Student Researchers
Visiting student researchers are not eligible to enroll in a research course and/or coursework, and will not receive academic credit from Caltech, but are required to check in with the Registrar's Office upon arrival to obtain a Caltech identification card. Visiting student researchers are also required to provide proof of health insurance for the duration of the visit. Additionally, international students are required to check in with the office of International Student Programs.

Students in this status are not eligible to receive a salary through the Institute payroll, and are not eligible for Caltech privileges that are extended to enrolled students. They may be reimbursed for research-related expenses only, but it is the Caltech faculty host's responsibility to ensure that the supporting grant can be used for such purposes and that there are no restrictions on spending. (Students receiving a salary through the Institute payroll and/or requiring a transcript to transfer academic credit should be appointed as special students. Short-term special students that do not need academic transcript credit must still enroll in a research class for a minimum of three units and will be billed tuition and fees based on the level of enrollment and length of stay with a minimum tuition equivalent to three units per term.

The visiting student researcher status is limited to short-term visits of one year or less and is not renewable.

Exchange Programs
Some academic options have formal exchange programs that they have arranged with other institutions. Exchange students must have a visiting student appointment, and the type of appointment will depend upon the terms of the agreement for the particular exchange program. These programs are administered by the option, and requests should be made directly to the Graduate Office following the same procedure for visiting students.

Graduate Residence
One term of residence shall consist of one term's work of not fewer than 36 units of advanced work in which a passing grade is recorded. Advanced work is defined as study or research in courses whose designated course number is 100 or above. If fewer than 36 units are successfully carried, the residence will be regarded as short by the same ratio, but the com-

pletion of a greater numberof units in any one term will not be regarded as increasing the res- idence. In general, the residency requirements are as follows: for Master of Science, a minimum of three terms of graduate work; for the degree of Engineer, a minimum of eight terms of graduate work; and for Doctor of Philosophy, a minimum of 12 terms of graduate work, four of which must be at the Institute.

Registration

Graduate students are required to register for each term of res- idence, whether they are attending a regular course of study, carrying research, doing independent reading, writing a thesis, or utilizing any other academic service or campus facility.

A graduate student must be registered for 36 or more units to be classified as a full-time student, but course loads greater than 45 units are common. A graduate student who registers for less than 36 units, or who undertakes activities related to the Institute aggregating more than 62 hours per week (in class, research, and teaching assistantship units), must receive approval from the dean of graduate studies. A petition for this purpose may be obtained from the Graduate Office website and must carry the recommendation of the option representative of the student's major option before submission.

Graduate students register during a two-week period each quarter. A late registration fee of $50 is assessed for failure to register on time. Graduate students with a bursar's bill balance of $1,500 or more may have a hold placed on their registration for the subsequent term the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Before registering, students should consult with their adviser. An adviser is assigned to each entering graduate student by the option representative. In most options, a new adviser is assigned when the student begins research. Only members of the professorial faculty may serve as advisers. With the approval of the dean of graduate studies, any graduate student whose work is not satisfactory may be refused registration at the beginning of any term by the division in which the student is doing his or her major work.

In registering for research, students should indicate the name of the instructor in charge, and should consult with him or her to determine the number of units to which the proposed work corresponds. At the end of the term, the instructor in charge may decrease the number of units for which credit is given if he or she feels that the progress of the research does not justify the original amount.

Students will not receive credit for courses unless they are properly registered. Students themselves responsible for making certain that all grades to which they are entitled have been properly recorded. Please note that graduate students who enroll in courses numbered below 100 will not receive credit for them unless the course(s) is specified in the requirements for a graduate degree as stipulated in the Catalog.

All changes in registration must be reported, on drop or add cards, to the Registrar's Office by the student. Such changes are governed by the last dates for adding or dropping courses as shown on the academic calendar on pages 4 and 5. A student may not withdraw from or add a course after the last date for dropping or adding courses without his or her option's consent, written approval from the instructor of the relevant course, and the approval of the dean of graduate studies.

If the withdrawal occurs after Add Day of any term, a W (standing for "withdrawn") will be recorded on the student's transcript for all courses in which the student is enrolled. A grade of W is not included in the computation of the student's grade-point average

Academic Year and Summer Registration

Most courses are taught during the three 12-week quarters that make up the academic year. However, doctoral-level students are required to maintain enrollment throughout the summer quar- ter. They are entitled to at least two weeks' annual vacation (in addition to Institute holidays), but they should arrange their vaca- tion schedules with their research advisers early in each academic year. Any questions should be referred to the dean of graduate studies.

All students in residence must be registered. There is no tuition charge for summer research units. To maintain full-time student status, 36 units must be taken in the summer quarter.

Sabbatical

Graduate students are required to maintain continuity in registration, full-time status, make satisfactory progress and be in residence, until all requirements for a degree are fulfilled. This includes the summer term. This means that students must be registered or on an approved leave from the Institute. Leaves may be approved for up to one year at a time. Leaves may be extended only with the concurrence of the advisor, option representative, and with permission of the dean of graduate studies. In the case of leaves for medical reasons, the petition must be recommended by the executive director, health and counseling center. Return from leave may be subject to conditions, including, in the case of medical leaves, the recommendation of the executive director, health and counseling center, or designee. Return from leave must be approved by the dean of graduate studies.

In general, international students who hold nonimmigrant visas must meet with an adviser in the International Student Programs Office to determine the impact that a sabbatical will have on their visa status.

Detached duty status maintains registration for a student doing research at an external location, such as a national laboratory or another academic institution, for an extended period. Reduced duty status maintains registration for a student who cannot carry a full load due to medical disability or pregnancy.

Pregnancy Leave

The Institute provides up to 8 weeks of paid leave to graduate students who are disabled due to pregnancy, childbirth or related medical conditions. Students on assistantships may be eligible for state disability insurance benefits, which will be integrated with the Institute paid leave to provide the student with a combined amount of no more than the employee's weekly gross pay. Pregnancy leave is a form of medical leave and requires students to complete the medical leave petition to leave which should be submitted and approved prior to the start of the leave. If a longer leave is required due to medical complications, students may petition to extend their leave without pay with approval of the dean of graduate studies. The Institute will also provide reasonable accommodations to students with pregnancy-related conditions consistent with federal and state law. Please consult with the Graduate Studies Office to learn more about the leave process and for answers to any questions.

Bonding Leave
Graduate students are provided six weeks of family bonding leave without pay. Family bonding leave without pay is available to the partner, if the partner is a graduate student at Caltech. Bonding leave requires submitting a petition for non-medical leave through the graduate studies office.

Petitions for Leave
Petition forms for leaves or reduced duty status, may be obtained from the graduate studies office website and must, before submission to the dean of graduate studies, carry the recommendations of the student's option representative and, where appropriate, the thesis adviser. Petitions for medical leave must also carry the recommendation of the executive director, health and counseling center. In case of a lapse in status, readmission must be sought before academic work may be resumed or requirements for the degree completed.

Registration is required for the term in which the thesis defense is undertaken, with the exception of the first week of each term, but is not normally allowed beyond the last date of the term. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms during the academic conferred in June, further enrollment as a graduate student is not permitted.

Return from Leave
Return from leave requires the recommendation of student's option representative and final approval of the dean of graduate studies. Return from leave for medical reasons additionally requires the recommendation of the executive director, health and counseling center, or designee.

Involuntary Leave
The dean of graduate studies may determine that it is necessary to place a student on an involuntary leave in a variety of circumstances, such as for the protection of the Institute community, for the personal safety or welfare of the student involved, or as a result of a disciplinary action or as an interim measure. The dean may impose an involuntary leave in appropriate circumstances, such as where a student's behav-

ior: (1) has, or threatens to, cause significant property damage; (2) significantly disrupts the functioning of the Institute community; (3) presents a substantial risk of harm to self or others; (4) indicates the student is unable or unwilling to carry out self-care obligations; or (5) violates a Caltech policy or the honor system. An involuntary leave also may be imposed when that the student requires a level of care from the Institute community that exceeds the resources and staffing that the Institute can reasonably be expected to provide for the student's well-being.

Individualized Assessment
When a student's behavior is associated with a physical or mental condition, the dean will conduct an individualized assessment. In making an informed decision to place a student on involuntary leave in such circumstances, the dean will consider relevant medical and/or other information available to him or her, including information provided timely by the student. The dean may consult with the executive director, health and counseling services and/or require a physical or mental evaluation from a health professional if the dean believes such an evaluation is necessary in order to make an informed decision. Students are expected, if necessary, to sign a release of information to facilitate discussions between Caltech and the health professional conducting the evaluation. The dean will also consider whether relevant risks factors can be eliminated or reduced to an acceptable level through reasonable accommodation.

Written Decision
The student will be advised in writing of the decision to impose an involuntary leave, any conditions for return, and whether the leave is for a specific term or is indefinite as to term. The dean may stipulate conditions that must be met before the student may return.

Emergency Leave
If the dean determines that a student's continued presence is likely to pose a substantial risk to the safety and well-being of the student or others, the dean may place the student on an emergency interim leave before a final determination is made. The dean will make reasonable attempts to meet with the student and consider relevant information, including medical information provided by the student, before deciding on an interim emergency leave. An emergency leave will remain in effect until a final decision has been made.

While on Leave
A student on involuntary leave may not attend classes, live in Institute housing, participate in Institute programs, or use Institute facilities during the term of the leave, unless approved in writing by the dean.

Return from Leave
A student on involuntary leave will not be allowed to return until the

dean makes a fact-specific assessment of the circumstances, considers relevant risk factors, and concludes that the student does not pose a significant disruption to the functioning of the Institute community and/or does not pose a substantial risk to the health and safety of the student or others. The dean will consider relevant information, including information provided by the student. In cases where a student has a physical or mental condition associated with the behavior triggering the leave, the dean will also consider whether the relevant risks can be eliminated by a reasonable accommodation. The student will be notified in writing if the dean determines that the student will not permitted to return from a leave.

Appeal

A decision by the dean of graduate studies to place a student on involuntary leave or a decision not to permit the student to return from involuntary leave may be appealed in writing within ten days to the vice president for student affairs (or his or her designee).

Guidelines for Graduate Student Advising

The relationship between a faculty adviser and graduate student should be founded on mutual respect and open communication. Advisers and students should discuss the nature of their working relationship early and continue this discussion throughout their period of collaboration to ensure mutually understood and compat- ible expectations. These discussions should be frequent and open, and should include not only work, research goals, and performance reviews, but also change of status, time for personal and family responsibilities, time off, and concerns about academic or work sit- uations. Both the student and adviser have the obligation to initiate meetings as necessary to ensure the success of therelationship.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

The graduate student–faculty adviser relationship should be guided by norms of fairness and professionalism. Both faculty and graduate students should avoid relationships that conflict with their respective roles and duties at Caltech. Both are bound by the prevailing policies prohibiting discrimination and harassment (Pages 68–70 and 91–107). Concerns relating to academic or work situations should be raised promptly between the persons directly involved, and handled informally if possible. Both students and advisers have the responsibility to raise and address concerns and conflicts promptly, honestly, and in a manner that conforms with academic integrity and professionalism. Caltech policy requires that students' concerns be addressed fairly and promptly, and prohibits retaliation or discrimination against students for appropriately voicing or raising a concern.

If a problem remains unresolved or if direct discussion is not possible, a student can seek assistance from division officers (e.g., option representatives) or the graduate deans. At any time, a student may request that discussions remain confidential. For more details about sources of assistance, consult the graduate option regulations (starting on page 319) and the Student Problem Resolution Process (page 50).

Part-Time Programs

Part-time graduate study programs at the Institute are for master's seeking graduate students who cannot devote full time to their studies and such students are subject to the following rules:

Degree Programs

- Applicants for the part-time master's program must submit a regular application form accompanied by a detailed plan for meeting the course requirements for the degree.
- Any research work done for academic credit shall be supervised by a Caltech faculty member.
- In general, students admitted to the part-time program are required to take at least 27 units of graduate course work or research each term.
- The part-time program is limited to two years of academic residence.
- Any option at the Institute retains the right to not participate in the program or to accept it under more stringent conditions.

Nondegree Programs

Caltech employees, both campus and JPL, are eligible to apply to take one or more graduate courses for credit. Participants in this program will not be considered to be working toward a Caltech degree, in contrast to the part-time program for graduate degrees described above, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree.

At least one month prior to the start of the term, the employee should have an initial discussion with the option representative of the option in which the course is to be taken. Application should be made to the Graduate Office by completing the special form provided for this purpose, and providing a transcript of academic work and one letter of recommendation. The employee must meet the prerequisites for the course, and must obtain the written permission of the instructor. The decision on admission to take each course will be made by the course instructor and the option representative, with final approval by the dean of graduate studies. Taking an additional course at a later time will require full reapplication. It is the employee's responsibility to arrange a revised work schedule with the appropriate supervisor. Approval of the employee's supervisor is required.

Part-time nondegree students are subject to the Honor System (see page 35) and are under the purview of the dean of graduate studies. They may take only courses numbered 100 or higher. Research courses are excluded from the program. For courses in which a letter grade is offered, these students may not register to receive a pass/fail grade in the course, nor can credit for the course be obtained by examination. The option may limit the number of nondegree students admitted to any one course.

Responsible Conduct of Research

Caltech researchers are expected to adhere to the highest professional standards in the conduct of research. Faculty members are charged by the Institute with the responsibility to safeguard the basic principles of research integrity, academic freedom, and public interest. Students are expected to also follow these same principles. When government funds are involved in the support of research, investigators are required to take specific steps to adhere to all rules and regulations of the government and sponsoring agencies. Students may be required to have specific training in research ethics and integrity as well as conform to standards established by research supervisors or their laboratories. There are two situations in which this is mandated by federal law.

National Institute of Health

Students that are funded through NIH grants, workwith human or vertebrate animal subjects, or are required as part of their academic option's curriculum, have to meet a NIH requirement for training in specified areas as described in the Caltech Guide to Sponsored Research. In order to meet the NIH requirement, Caltech requires that all trainees supported by NIH funds take Biology course 252 "Responsible Conduct of Research."

National Science Foundation

Training in Responsible Conduct of Research is also required of students funded on NSF awards, including the GRFP program. In order to satisfy the NSF mandate, Caltech requires that students supported from NSF funds as described above shall take the online course on Research Ethics Education (CITI).

If a student can document having passed a similar, qualifying program at another institution, Caltech may accept that in lieu of completing Caltech's program. You must submit documentation in the form of a transcript or certificate to the Graduate Office to receive credit for previous work. A passing grade in Bi 252 is an acceptable alternative to passing the CITI online Responsible Conduct of Research course.

Conflict of Interest and Commitment of Graduate Students

The Institute has a long-standing philosophy that all graduate students should be given the opportunity to be completely focused on graduate studies and research. This is one of the unique aspects of Caltech's graduate school and a key factor in the high level of productivity and accomplishment by our graduate students. To enable this, the faculty and Institute provide financial aid in the form of fellowships, tuition scholarships, graduate teaching, and research assistantships. The stipend and salary levels for students are modest but sufficient for economical students to live debt-free during their graduate studies. The financial support provided by the Institute and the requirements for continuous enrollment also enable almost all students to complete the degree programs in a timely manner.

In turn, the Institute expects that graduate students should be 100 percent committed to graduate studies while enrolled in a gradu- ate program. Graduate students are expected to be continuously enrolled full-time, year-round, until they complete their degree program. In addition, graduate students should not accept employ- ment, start or run a business, or engage in any activity inside or outside of the Institute that creates a conflict of commitment with their full-time, degree-seeking status.

Exceptions

There are some very limited exceptions to this policy. The Institute encourages extracurricular activities that provide service to the community and do not impact the student's academic prog- ress or full-time status. The Institute also recognizes that some students desire to gain experience as instructors or work in an edu- cational or research setting outside of Caltech.

Outside Employment

With the permission of the dean of graduate studies, students may accept limited-duration, part-time employment for these purposes (see Financial Assistance, page 312). Students must declare to the dean of graduate studies all external funding, including fellowships, awards, or employment, part- or full-time, which supports their academic activities/research. The Institute may adjust Institute financial aid allocated accordingly to maintain the stipend within the Institute guidelines and to recover tuition from outside sources whenever possible. A student's financial aid and/or Institute salary may be reduced if the income is significant, and in the case of long-term, unreported employment activities, the student may be asked to repay financial aid.

Students may not hold a position of line responsibility in an outside enterprise for pay or profit. Students must have the approval of their adviser, the option representative, and the dean of graduate studies in order to engage in any outside employment activities.

International students on a visa are further required to consult with the office of International Student Programs to determine eligibility. Students must provide official documenta- tion of the financial award or salary, as well as submit a request to the Graduate Office before accepting any employment. Permission to engage in outside employment is contingent on the student maintaining satisfactory academic progress as determined by the dean of graduate studies in consultation with the adviser and option representative.

Non-Paid Activities

Students must have the approval of their adviser, the option representative, and the dean of graduate studies in order to engage in or continue in any outside activities wherein the time committed to those activities may impact the student's progress toward comple- tion of his or her degree.

Leave of Absence
Students who work full-time off campus in a commercial organization are advised to take a leave of absence (non-medical sabbatical). They will not be enrolled during this time, and the "clock" will stop on their graduate career. Taking a leave of absence in order to work requires the endorsement of the adviser and permission of the dean of graduate studies. A leave of absence is always required when the job is not research-related. Students who need to stop their studies to address health issues should take a medical leave of absence, which requires the endorsement of the health and counseling centers as well as the permission of the dean of graduate studies.

Detached Duty
In some cases, a student may be employed by a laboratory or research institute but still engaged in research directly related to his or her degree program. Another situation is that a student may be invited to be a visiting researcher at another university, or the student may need to be working with a faculty member who has left Caltech and is working at another institution.

Students may go on detached duty rather than on leave of absence if the adviser and dean of graduate studies approve and there is documentation of a research program and appropriate mentoring. Students who are in the advanced stages of their study and plan to complete their graduate studies while on detatched duty should have completed their residency requirements and advanced to candidacy prior to moving to the host institution.

The student should submit the documentation and a petition form to the Graduate Office. Students on detached duty are

still enrolled as full-time students but are in residence at another location. They may be paid by Caltech or through another orga- nization. It is the student's responsibility to continue to be in good standing, and registered and in full-time status while on detached duty. Detached duty petitions are usually only valid for a limited time, less than one year, and can be renewed upon request.

Consulting and Other Entrepreneurial Activities
Graduate students are sometimes approached to perform paid consulting or are inspired to be entrepreneurs. In these cases, students have to be exceptionally careful not to create conflicts of commitment or conflicts of interest through these activities. Students considering these activities should familiarize themselves with the Caltech policies on conflict of interest, outside employment or business activity, and the Caltech ethics handbook. Students may not engage in any consulting activities that interfere with their primary graduate student activities of learning and research. Scrupulous care must be taken to ensure that Caltech's

name and its letterhead are used neither directly in any correspondence between the student and the company the student wishes to consult for, nor in any reports that student may submit to the company.

Of particular concern are students consulting or accepting employment from a company in which their adviser or other Caltech faculty member is directing a student's research and has a significant interest or is a paid consultant. In such cases, the division chair must approve any student involvement in the activities performed for the company. The student must submit a written disclosure, and a conflict management plan will be put in place.

Graduate students should not enter into any consulting or employment agreement with intellectual property encumbrances or confidentiality provisions that are in conflict with the student's commitments to Caltech or that may compromise progress toward his/her thesis.

Please refer to the Graduate Office website for the complete policy and regulations regarding conflicts of commitment and interest. If there are any questions about the propriety of any outside activity or agreements, this should be discussed with the Graduate Office and, if necessary, the Office of Research Compliance and the Office of the General Counsel.

Working at Special Laboratories

- Students who desire to take advantage of the unique oppor tunities available at one of the special laboratories (e.g., JPL) for Ph.D. thesis work may be allowed to do so, provided that they maintain good contact with academic life on campus, and the laboratory involved commits financial support for the duration of the thesis research, and provided that all Caltech graduate thesis research carried out at a special laboratory is under the supervision of Caltech faculty members.
- A student's request to carry out thesis work at a special laboratory should be formally endorsed by the appropriate committee of his or her option and by the special laboratory, on a petition submitted through the option representative to the dean of graduate studies. The special laboratory should recognize its commitment of special equipment or any other resources required for the thesis work. Approval by the special laboratory should also indicate that the thesis topic is a sensible one, and that it is not likely to be preempted by the laboratory.
- A student may take similar advantage of unique opportunities at a corporate or governmental research and development facility under the same conditions, providing that there exists a formal written agreement between the R&D facility and the student's thesis adviser, and that advance written approval is obtained from the dean of graduate studies. Such curricular practical training may in some cases involve full-time emplopment at the laboratory for a limited period of time for the purpose of engaging in the essential data collection that is integral to a student's doctoral dissertation. Typically, such students

who are not in a local laboratory are placed on detached duty status.

- Employment by a special laboratory of a graduate student for work not connected with his or her thesis should be regarded as equivalent to other outside employment.

Exchange Program with Scripps Institution of Oceanography

An exchange program has been established with the Scripps Institution of Oceanography (SIO), University of California, San Diego, permitting Caltech graduate students to enroll in and receive credit for graduate courses offered by SIO. Arrangements should be made through the student's major option and the Graduate Office. The student must obtain the advance approval of the instructors of courses to be taken at SIO. In some cases, when it is in the best interests of the student, arrangements may be made for the student to be temporarily in full-time residence at SIO.

Thesis research done partly at SIO may be arranged directly by the student's option and the staff of appropriate research labo- ratories at SIO, without the necessity of enrolling for SIO courses designated for research; in this case the student will continue to be under the supervision of his or her Caltech thesis adviser and will enroll for Caltech research units.

GENERAL REQUIREMENTS FOR GRADUATE DEGREES

Degree of Master of Science

The Master of Science degree is a professional degree designed to prepare a student for teaching, for further graduate studies, or for more advanced work in industry. Detailed requirements are based primarily on professional studies, and the program should be planned in consultation with the faculty in the appropriate discipline. Under normal circumstances, the requirements for the M.S. degree can be completed in one academic year. Students must declare candidacy for the M.S. degree no later than the academic year in which the final degree requirements have been met or upon separation from the Institute. Students who are pursuing a doctoral degree and obtain a M.S. along the way, must declare candidacy for the M.S. no later than two weeks prior to conferral of the Ph.D.

A student who enters the Institute holding a master's degree from another institution will not normally be awarded a second master's degree in the same field. A student may not normally be awarded two master's degrees from the Institute.

Special regulations for the master's degree are listed under each graduate option. Several options do not offer an M.S. degree except in special circumstances.

Residence and Units of Graduate Work Required. At least one academic year of residence at the Institute and a minimum of 135 units of graduate work at the Institute subsequent to the baccalau- reate degree are required for the master's degree. Included in these units are at least 27 units of free electives or of required studies in the humanities numbered 100 or above. Advanced courses taken while enrolled as a Caltech undergraduate student in excess of the bachelor's degree requirements may be counted toward the mas- ter's degree requirements with the approval of the academic option representative and the dean of graduate studies.

To qualify for a master's degree, a student must complete the work indicated in the section on special regulations for his or her option with a grade-point average for the approved M.S. candidacy courses of at least 1.9.

In special cases, with the approval of the instructor, option representative, and the dean of graduate studies, courses taken else- where before enrollment at the Institute may be offered in place of specifically required courses. An examination may be required to determine the acceptability of such courses. Course credit, if granted, shall not count toward the 135-unit and residency requirements.

Joint B.S./M.S. Degree. In exceptional cases, undergraduate students may pursue a joint B.S./M.S. program of study. Several options do not allow a joint B.S./M.S. degree. Students should contact the graduate option representative to find out if the joint B.S./M.S. degree is possible in a particular option. Such students must follow the normal procedures for admission to the M.S. pro- gram in the option of their choice. Students attending courses or carrying out research toward an M.S. degree before completion of their B.S. degree requirements will be considered as undergraduate students and will not be eligible for graduate financial aid, graduate housing, or other graduate student privileges.

Admission to M.S. Candidacy. Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she should complete a proposed plan of study, which must have the approval of the option representative and, if a thesis is required, of his or her research adviser. Some options require a thesis or research report in addition to course requirements. The thesis or research report must be approved by the research adviser no later than two weeks before the degree is to be conferred. This approved plan of study will constitute the requirements for the degree. Any modifications must be approved by the option representative at least two weeks before the degree is to be conferred.

Students enrolled for the joint B.S./M.S. program must com- plete a minimum of 486 units for the B.S. program and a minimum of 135 units for the M.S. program with no overlapping of courses.

Engineer's Degree

Engineer's degrees are awarded in exceptional circumstances. The work for an engineer's degree must consist of advanced studies and research in the field appropriate to the degree desired. It must conform to the special requirements established for that degree and should be planned in consultation with the members of the faculty concerned. Students who have been admitted to the terminal master's degree and wish to pursue further studies leading toward either the engineer's or the doctor's degree must file a petition (and in some cases must file a new application) to continue graduate work toward the desired degree. Students who have received an engineer's degree will not in general be admitted for the doctor's degree.

Residence. At least eight terms of graduate residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for an engineer's degree. Of these, at least three terms must be at Caltech. It must be understood that these are minimum requirements, and students must often count on spending a some- what longer time on graduate work.

To qualify for an engineer's degree, a student must complete the work prescribed by his or her supervising committee with a grade-point average of at least 1.9. Research work and the prepa- ration of a thesis must constitute no fewer than 55 units. More than 55 units may be required by certain options, and the student should determine the particular requirements of his or her option when establishing a program.

Admission to Candidacy. Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she must complete a proposed plan of study and, in consultation with the chair of the appropriate division, will select a committee of three members of the faculty to supervise the student's work and to certify its satisfactory completion. One of the members of the committee should be in a field outside the student's major field of study. The student should then consult with this committee in planning the details of his or her work. The plan of study shall then constitute the requirements for the degree. Any modifications must be approved by the option representative at least two weeks before the degree is conferred.

The student will be admitted to candidacy for the degree when the supervising committee certifies (a) that all the special require- ments for the desired degree have been met, with the exception that certain courses of not more than two terms in length may be taken after admission to candidacy; (b) that the thesis research has been satisfactorily started and can be finished at the expected date; (c) that the candidate demonstrates competence in oral and written English.

Admission to candidacy should be obtained by the midpoint of the term in which the degree is to be granted, but no later than the academic year in which the final degree requirements have been met or upon separation from the Institute.

Thesis. At least two weeks before the degree is to be conferred, each student is required to submit his or her thesis in accordance with the regulations that govern the preparation of doctoral dis- sertations. These regulations may be obtained from the Graduate Office website.

The use of "classified" research as thesis material for any degree will not be permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

Examination. At the discretion of the option in which the degree is desired, a final examination may be required. This examination would be conducted by a committee appointed by the candidate's supervising committee

Degree of Doctor of Philosophy

The degree of Doctor of Philosophy is conferred by the Institute primarily in recognition of breadth of scholarship, depth of research, and the power to investigate problems independently and efficiently, rather than for the completion of definite courses of study through a stated period of residence. The work for the degree must consist of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering. In addition, the candidate must have clear self-expression in both oral and written English.

Subject to the general supervision of the Committee on Graduate Study, the student's work for the degree of Doctor of Philosophy is specifically directed by the division in which he or she has chosen the major subject. Each student should consult with his or her division concerning special divisional and option requirements.

Admission. With the approval of the dean of graduate studies, students are admitted to graduate standing by the option in which they choose their major work toward the doctoral degree. In some cases, applicants for the doctorate may be required to complete requirements for the master's degree first; however, this is not a general prerequisite for the doctorate. Students who have received an engineer's degree will not, in general, be admitted for the doctoral degree.

A student who holds a Ph.D. degree from another institution will not normally be admitted to graduate standing at Caltech to pursue a second Ph.D. degree. A student will not normally be awarded two Ph.D. degrees from the Institute.

Minor Programs of Study. The Institute does not require a minor for the Ph.D. degree, but the individual options may have minor requirements as part of their requirements for the major.

A student may undertake a minor program of study in most pptions as specified in this catalog under the section "Special Regulations of Graduate Options." Completion of a minor program of study is recognized on the Ph.D. diploma by the statement "…and by additional studies constituting a minor in [name of option]."

A minor program of study should be at a level of study in the minor substantially beyond that typically acquired by students as part of their major requirements. Most options require 45 units or more, including at least one 200-level course and a coherent program of the supporting 100-level courses. The faculty of the minor option may approve a proposed minor program on the basis of overall class performance and/or by an oral examination.

Detailed requirements for minor options are listed under the individual options. Students cannot use courses required by their major option in fulfillment of the minor requirement.

Residence. At least twelve terms (three academic years) of residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for the doctorate. Of this, at least four terms must be in residence at the Institute. It should be understood that these are minimum requirements, and students must usually count on spending a somewhat longer time in residence. A student whose undergraduate work has been insufficient in amount or too narrowly specialized, or whose preparation in his or her special field is inadequate, should plan upon spending increased time in work for the degree.

However, no student will be allowed to continue work toward the doctoral degree for more than twenty-four academic terms of graduate residence, without a petition approved by the dean of graduate studies. This petition must include a plan and schedule for completion, agreed upon and signed by the student, the research adviser, and the option representative.

Registration. Continuity of registration must be maintained until all requirements for the doctorate degree have been completed, with the exception of authorized sabbaticals. Registration is required for the term in which the thesis defense is undertaken.

Admission to Candidacy. On the recommendation of the option concerned, the dean of graduate studies will admit a student to candidacy for the degree of Doctor of Philosophy after the student has been admitted to work toward the doctorate and has been in residence at least one term thereafter; has initiated a program of study approved by the major option and, if needed, by the minor option; has satisfied by written or oral examination the several options concerned, or otherwise shown that he or she has a comprehensive grasp of the major and minor subjects and of subjects fundamental to them; has demonstrated the ability for clear self-expression in both oral and written English; and has shown ability in carrying on research in a subject approved by the option concerned. Option regulations concerning admission to candidacy are given in a later section. Members of the Institute staff of rank higher than that of assistant professor are not admitted to candidacy for a higher degree.

Depending upon option regulations, candidates will either be assigned a candidacy committee by the option representative or must independently select appropriate members to serve on the examination committee. An examination committee should consist of a minimum of three voting members, two of whom must be Caltech faculty. Exceptions to this rule must be approved by the dean of graduate studies in advance of the candidacy examination. The student should ensure that all members of the examining committee are available during the examination period and that they are willing to provide timely and appropriate feedback. Admission to candidacy must be obtained before the close of the second term in which the degree is to be conferred. The student is responsible for seeing that admission is secured at the proper time. A student not admitted to candidacy by the end of the twelfth term of graduate residence at the Institute must petition the dean of graduate studies for permission to register for further work.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

Candidacy (and permission to register) may be withdrawn by formal action of the option from a student whose research is not satisfactory, or for other compelling reasons. However, the option must petition through its division chair to the dean of graduate studies before taking such action.

Final Examination. Each doctoral candidate shall undergo broad oral examination on the major subject, the scope of the thesis, and its significance in relation to the major subject. The examination, subject to the approval of the dean of graduate studies, may be taken after admission to candidacy whenever the candidate is pre- pared; however, it must take place at least three weeks before the degree is to be conferred.

The examination may be written in part, and may be subdivided into parts or given all at one time at the discretion of the options concerned. The student must complete the exam notification not less than two weeks before the date of the examination. An examination committee should consist of a minimum of four voting members, three of whom must be Caltech faculty. Exceptions to this rule must be approved by the dean of graduate studies in advance of the defense.

Thesis. The candidate is to provide a draft copy of his or her completed thesis to the members of the examining committee at least two weeks before the final oral examination. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until the thesis is submitted in completed form, i.e., ready for review by the dean, the members of the examining committee, and the Graduate

Office proofreader. Registration is required for the term in which the thesis defense is undertaken, but is not normally allowed beyond the last date of the term. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms following the thesis defense. A student not receiving Caltech funding, may petition the dean of graduate studies for reduced tuition charges if the student supplies a copy of the thesis, schedules the examination, and schedules the Ph.D. examination prior to the third Friday of the term in which the examination will be taken.

The last date to upload the final, corrected thesis is the fifth week of the succeeding term if the candidate defended his or her thesis during the previous summer or the first or second terms; or two weeks before the degree is to be conferred if the candidate defended his or her thesis during the month of May. It is required that all doctoral candidates submit an electronic copy of their dissertation, which the Caltech Library System will then archive and make available online, as part of the Networked Digital Library of Theses and Dissertations (NDLTD), an international organization that allows researchers to globally search a database of electronic theses and dissertations. For special option regulations concerning theses, see specific graduate options.

Before uploading the final, corrected thesis, the candidate must obtain approval of the thesis by the option representative of his or her option and the members of the examining committee.

With the approval of the option concerned, a portion of the thesis may consist of one or more articles published jointly by the candidate and members of the Institute staff or other coauthors. In any case, however, a substantial portion of the thesis must be the candidate's own exposition of his or her own work.

The use of "classified" research as thesis material for any degree is not permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

Regulations and directions for the preparation of theses may be obtained from the Graduate Office website, and should be followed carefully by the candidate. Thesis templates are also available on the Library website.

Satisfactory Academic Progress

In order to continue in a degree program and to receive finan- cial aid at Caltech, graduate students must maintain satisfactory academic progress toward completion of their degree. Continuity of registration must be maintained until all requirements for the degree being sought have been completed, with the exception of authorized sabbaticals.

The Master of Science degree requires at least three terms of residence at the Institute and a minimum of 135 units of graduate work with a grade-point average of at least 1.9. Under normal circumstances a master's degree cannot take more than two years without a petition approved by the dean of graduate studies.

The engineer's degree must consist of advanced studies and research in the field appropriate to the degree desired. At least eight terms of graduate residence are required with a minimum 1.9 overall grade-point average. The engineer's degree cannot take more than twelve terms to complete without a petition approved by the dean of graduate studies.

For the doctorate degree, at least twelve terms of residence are required, but the necessary study and research typically can be completed in less than six years. The work for the degree consists of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering.

The requirements for each degree include special regulations established by each option and detailed in the Institute Catalog for the year of initial registration. Many options require a C grade or better in particular courses or groups of courses. Hence, a limited number of courses may be repeated while still maintaining a status of satisfactory academic progress and would count toward the 36-unit-per-term requirement. A full-time graduate student must register for (and complete) 36 units per term, including the summer term. Approval of the dean of graduate studies is required before dropping any course that brings a student below 36 units. The treatment of incomplete grades and withdrawals is specified on pages 41–45. Satisfactory academic progress is checked each academic term by the Graduate Office.

The special regulations for the options typically include the completion of specific courses, oral and/or written examinations, petitions, research requirements, etc., by specific times. Satisfactory academic progress is judged by the options against these regulations, and revocation of permission to register may be rec- ommended by the option to the dean of graduate studies prior to or in response to the student's petition for admission to candi- dacy. Further, even after admission to candidacy, the candidacy (and permission to register) may be withdrawn by formal action of an option for a student whose research is not satisfactory, or for other compelling reasons. However, the option must petition through its division chair to the dean of graduate studies before taking such action.

A doctoral student who has not been admitted to candidacy by the beginning of the fourth year (12 terms) must petition the dean of graduate studies for permission to register for further work. In addition, no doctoral student will be allowed to register for more than 24 terms without approval of a petition by the dean of gradu- ate studies.

This petition must include a plan and schedule for completion, agreed upon and signed by the student, the thesis advising committee, and the option representative.

GRADUATE EXPENSES

The tuition and fees charge for all students registering for graduate work is currently $45,264 per academic year, payable at the beginning of each term, fall (9/28/15), winter (1/4/16), and spring (3/28/16). Graduate students who cannot devote full time to their studies are allowed to register only under special circumstances. Students desiring permission to register for fewer than 36 units must therefore petition the dean of graduate studies for an underload.

The payment of tuition by graduate students is required (a) without reference to the character of the work by the student, which may consist of research, independent reading, or writing a thesis or other dissertation, as well as attendance at regular classes; (b) without reference to the number of terms in which the student has already been in residence; and (c) without reference to the status of the student as an appointee of the Institute, except that members of the academic staff of rank of instructor or higher are not required to pay tuition.

Unpaid Bills. All bills owed the Institute must be paid when due. Any student whose bills are past due may be refused registration for the following term. All graduate students with an outstanding bursar's bill balance of $1,500.00 or more will have a hold placed on their registration for the subsequent term the day before online registration opens. Official transcripts and diplomas will not be released until the bursar's account is paid in full.

Caltech ID Card Charges. If a graduate student owes more than $1,500.00, the student's charging privileges will be suspended. Charging privileges will be reactivated once students have paid their bill in full with the Bursar's Office.

Expense Summary 2015–16

General:

Tuition and fees	$45,264.00

Other:

General Deposit	$100
Books and supplies (approx.)	$1,323.00
Room:	

Catalina apartments

4 bedroom apt. $557.00 per person per month (plus utilities)
2 bedroom apt. $661.00 per person per month (plus utilities)
1 bedroom apt. $1,121.00 per apt. per month (plus utilities)

Contact Bursar's Office for audit fee.

Fees are subject to change at the discretion of the Institute.

Fees for Late Registration. Registration is not complete until the student has registered for a program approved by his or her adviser and has paid tuition and other fees. A penalty fee of $50 is assessed for failure to register within five days of the scheduled dates.

Honor System Matters. Monies owed to the Institute resulting from a disciplinary matter may be collected through the Bursar's Office, at the request of the Office of Graduate Studies.

Housing Facilities. The Catalina Central complex provides approximately 152 single rooms in four-bedroom furnished units. Another, Catalina North, has 156 single rooms in two-bedroom furnished units, and Catalina South has 78 single rooms in two-bedroom furnished units, and 29 one-bedroom furnished units. These apartments are also available to married students.

Rates for housing vary, depending upon the accommodations and services provided. A contract is required to live in these houses for the academic year. Complete information can be obtained at http://www.housing.caltech.edu.

There is one Residential Life Coordinator (RLC) and three Resident Associates (RAs) in the Catalina Complex. An RLC is a specially trained full-time university employee, specializing in college student development, community building, counseling, and crisis intervention. The RLC supervises the RAs on programming and overall student wellness. The RLC also assists Housing with the management and daily operations of the complex. There are also Catalina Community Associates (student volunteers) who work with the RLC and RAs on programming and community building in the Catalinas.

The Institute also owns a limited number of apartments and single-family houses that are available for rental, on a lease basis, to single or married graduate students or graduate students with families. Because of limited availability, there is a waiting list for these properties. For additional information and sign-up forms, go to http://www.housing.caltech.edu.

Students preferring to live in non-Institute housing typically pay approximately $550–$600 per month in rent for a shared apartment, and somewhat more for a private apartment. Please note that the Institute cannot make negotiations for individual housing off campus.

Dining Facilities. Graduate students are granted the privilege of joining the Athenaeum (faculty club), which affords the possibility of contact with fellow graduate students and with others using the Athenaeum, including the Associates of Caltech, distinguished visitors, and members of the professional staffs of the Huntington Library and the California Institute of Technology.

The Chandler Dining Hall, located on the campus, is open Monday through Friday. Breakfast, lunch, and snacks are served cafeteria style. Café at Broad is open for lunchr, Monday through Friday.

Health Services. Health services available to graduate students are explained in section one of this catalog.

FINANCIAL ASSISTANCE

Caltech offers in each of its options a number of fellowships, tuition scholarships, and graduate assistantships. In general, tuition scholarships may be for full or partial tuition charges; assistantships provide stipends; and fellowships often provide both tuition scholarship awards and stipends. Graduate assistants are eligible to be considered for special tuition awards.

Appointments to fellowships, scholarships, and assistantships are decided yearly by the student's academic option.

Graduate students receiving any form of financial award from the Institute are required to report to the dean of graduate studies any financial aid from other sources. With prior written approval from the dean of graduate studies, students may be allowed to accept outside employment if the time commitment does not interfere with their graduate studies. The number of hours per week spent on outside employment must be reported to the dean of graduate studies.

Graduate Assistantships

Graduate assistants help with teaching, laboratory work, or perform research of a character that affords useful academic experience while permitting a full academic schedule of courses. The specific research and teaching obligations of graduate assistants are agreed upon with the adviser.

Caltech graduate students often receive a combination of teaching and research assistantships; however, the total work commitment cannot exceed 20 hours per week during the academic year. Summer appointments can be greater, with assignments up to 40 hours per week. A graduate student who undertakes activities related to the Institute aggregating more than 62 hours per week (in class, research assistantship, and teaching assistantship hours) must petition the dean of graduate studies.

Graduate assistant stipends are based on four separate 12-week quarters, resulting in a 48-week pay period, paid on the last pay period of the month. Students are also entitled to two weeks of annual vacation and Institute holidays. Students should prearrange their vacation schedule with their adviser and, when appropriate, may arrange longer or shorter appointments depending upon departmental policy and the arrangements agreed upon between the adviser and the student. In addition, when necessary, graduate assistants may arrange for short-term medical leave (including pregnancy). Any questions should be referred to the dean of graduate studies.

Teaching Assistantships

A full teaching assistantship usually requires 20 hours per week to be devoted to teaching and to the related activities of class preparation, grading, and consulting with students. In general, teaching obligations are confined to the 12 weeks of the academic terms, excluding summer. A student may not, without advance permission from the dean of graduate studies, be a teaching assistant for a course in which he or she is enrolled and receive credit. Only teaching assistants with good oral English are permitted to teach sections. Students may demonstrate competence by passing the English proficiency screening during orientation, enrolling in and passing ESL 101, or subsequently scoring at least 50 on the standardized NTS (National Testing Service) SPEAK test before admission to candidacy.

All teaching assistants are required to attend teaching-assistant training before payment can be processed. Training sessions occur in the first week of the fall term, typically during orientation, and at least once per term for continuing students, including undergraduate students with teaching responsibilities.

Teaching assistants must familiarize themselves with Caltech's policy on harassment (see pages 91-107). Classes should foster academic achievement in a "hassle-free" environment. Teaching assistants should not attempt to date a student in their class, and should disqualify themselves from teaching a section in which a spouse or current partner is enrolled.

Research Assistantships

Research assistantships typically are 20 hours per week during the academic year, but can be as much as 40 hours per week during the summer. The specific duties are decided upon by the adviser.

Graduate Scholarships, Fellowships, and Research Funds

Students are strongly encouraged to apply for scholarships and fellowships from federal and private agencies and organizations to support their graduate studies. In addition, the Institute offers a limited number of endowed fellowships and scholarships for tuition and/or stipends to graduate students of exceptional ability.

Loans

Several types of loans are available to graduate students. To qualify for any of these, a student must demonstrate financial need and must maintain satisfactory academic progress in the course of study for which he or she is enrolled. Application forms and further information are available from the Financial Aid Office.

Refund and Repayment Policy

Caltech has established an equitable refund policy for students who find it necessary to withdraw or take a sabbatical from the Institute.

Students who officially withdraw or take a sabbatical from the Institute during an academic term may receive a tuition refund (see pages 189–193). Students living in Caltech housing may also be eligible for a partial refund from the Housing Office.

When granting refunds to financial aid recipients or graduate assistants, it is Caltech's policy to return the refund, in most cases, to the original account.

PRIZES

Tom Apostol Award for Excellence in Teaching in Mathematics

In 2010, the mathematics option set up the Apostol Teaching Award in honor of Tom Apostol, who was a great teacher at Caltech for over 50 years. Three to five awards are given each year to recognize excellence in teaching by our graduate and undergraduate teaching assistants.

Charles D. Babcock Award

The Charles D. Babcock Award recognizes a student whose achievements in teaching (or other ways of assisting students) have made a significant contribution to the aeronautics department. The criteria for the award selection are as follows: The award can be made as unscheduled support for a graduate student associated with aeronautics, e.g., for travel to a technical meeting for professional advancement. All aeronautics-associated students are eligible, with preference given to those in the structures and solid mechanics group. The award may be made yearly, as merited.

The timing of the award will be as special recognition warrants.

The Charles D. Babcock Award was established in 1992 in memory of Charles D. Babcock, who was professor of aeronautics and applied mechanics until 1987; he served aeronautics as option representative and the Institute as vice provost.

William F. Ballhaus Prize
A prize will be awarded for an outstanding doctoral dissertation in aeronautics, to be selected by the aeronautics faculty. This award is made possible by a gift from Dr. William F. Ballhaus, a California Institute of Technology alumnus who received his Ph.D. in aeronautics in 1947.

Bohnenblust Travel Grants in Mathematics
Special grants may be awarded to outstanding graduate students in mathematics to enable them to travel in the United States or abroad to further their mathematical education. The mathematics faculty established these awards in 1978 to honor H. F. Bohnenblust, who served Caltech as professor of mathematics, executive officer for mathematics, and dean of graduate studies. Application forms and further details are available in the mathematics office, 253 Sloan.

Rolf D. Buhler Memorial Award in Aeronautics
An award is made annually to a student in the aeronautics master's program whose academic performance was exemplary and who shows high potential for future achievements at Caltech.

The Rolf D. Buhler Memorial Award in Aeronautics was established in 1990 in memory of Rolf Buhler, a 1952 graduate of GALCIT and professor of space flight at the Technical University of Stuttgart in Germany.

W. P. Carey & Co., Inc., Prizes in Applied Mathematics
Prizes will be awarded by a faculty committee in applied mathematics for outstanding doctoral dissertations. If there is no appropriate candidate, then the awardee can be chosen from pure math. These awards have been made possible by gifts from William Polk Carey and from W. P. Carey & Co., Inc.

Centennial Prize for the Best Thesis in Mechanical and Civil Engineering
Awarded each year to a candidate for the degree of Doctor of Philosophy in applied mechanics, civil engineering, or mechanical engineering whose doctoral thesis is judged to be the most original and significant by a faculty committee appointed annually by the executive officer for mechanical and civil engineering. The prize consists of a citation and a cash award and was established with gifts from alumni following the Mechanical Engineering Centennial Celebration in 2007.

Richard Bruce Chapman Memorial Award
A prize will be awarded annually to a graduate student who has distinguished himself or herself in research in the field of fluid dynamics.

Bruce Chapman was awarded an M.S. from Caltech in 1966 and a Ph.D. in 1970, both in engineering science. This award has been established in his memory by his family and friends.

Milton and Francis Clauser Doctoral Prize
An annual prize is awarded to the Ph.D. candidate whose research is judged to exhibit the greatest degree of originality as evidenced by its potential for opening up new avenues of human thought and endeavor as well as by the ingenuity with which it has been carried out. The Milton and Francis Clauser Doctoral Prize is made possible by gifts from the family and friends of these twin alumni, who received bachelor's degrees in physics in 1934, master's degrees in mechanical engineering in 1935, and doctor's degrees in aeronautics in 1937.

Donald Coles Prize in Aeronautics
The Donald Coles Prize will be awarded to the graduating Ph.D. student in aeronautics whose thesis displays the best design of an experiment or the best design for a piece of experimental equipment.

Demetriades-Tsafka-Kokkalis Prize in Biotechnology or Related Fields
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in biotechnology or related fields at the Institute in the preceding 12 months. Winners are selected by the bioengineering faculty. This award has been made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Demetriades-Tsafka-Kokkalis Prize in Entrepreneurship or Related Fields
Awarded annually for the best business plan or proposal, start-up, thesis, publication, discovery, or related efforts by student(s) in entrepreneurship or related fields at the Institute in the preceding 12 months. This prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Demetriades-Tsafka-Kokkalis Prize in Environmentally Benign Renewable Energy Sources or Related Fields
Awarded annually to a Ph.D. candidate for the best thesis, publication, discovery, or related efforts in benign renewable energy sources or related fields at the Institute in the preceding 12 months. The prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Demetriades-Tsafka-Kokkalis Prize in Nanotechnology or Related Fields
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in nanotechnology or related fields at the Institute in the preceding 12 months. This prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Demetriades-Tsafka-Kokkalis Prize in Seismo-Engineering, Prediction, and Protection
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in seismo-engineering, prediction, and protection in the preceding 12 months. Winners are selected by the seismo-en-

gineering faculty. The prize is made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Constantin G. Economou Memorial Prize
Awarded to a chemical engineering graduate student distinguished by outstanding research accomplishments and exemplary attitude while fulfilling candidacy requirements for the Ph.D. degree.

Everhart Distinguished Graduate Student Lecture Series
The Everhart Lecture Series is a forum to encourage interdisciplinary interaction among graduate students and faculty, to share ideas about recent research developments, problems, and controversies, and to recognize the exemplary presentation and research abilities of Caltech's graduate students. Lecturers discuss scientific topics at a level suitable for graduate students and faculty from all fields while addressing current research issues. Each fall, three graduate-student lecturers are selected to present their work as part of the Everhart Lecture Series based on each student's dynamic speaking skills, which capture the attention of and convey research material clearly to a diverse technical audience; ability to communicate his or her research field's broader importance; and impact on the scientific community through his or her research. Speakers receive an honorarium and recognition at graduation.

Lawrence L. and Audrey W. Ferguson Prize
Awarded to the graduating Ph.D. candidate in biology who has produced the outstanding Ph.D. thesis for the past year.

Henry Ford II Scholar Awards
The Henry Ford II Scholar Awards are funded under an endowment provided by the Ford Motor Company Fund. Each award will be made annually either to the engineering student with the best academic record at the end of the third year of undergraduate study, or to the engineering student with the best first-year record in the graduate program. The chair of the Division of Engineering and Applied Science names the student to receive the award.

Graduate Deans' Award for Outstanding Community Service
This award is made annually to a Ph.D. candidate who, throughout his or her graduate years at the Institute, has made great contributions to graduate life and whose qualities of leadership and responsibility have been outstanding.

Hans G. Hornung Prize
This prize is awarded for the best oral Ph.D. defense presentation by a student advised by an aerospace faculty member. The committee to determine the winner is made up of current aerospace engineering students who attend the talks in order to make their recommendation.

Scott Russell Johnson Prize for Excellence in Graduate Study in Mathematics
Four prizes will be given to continuing graduate students for excellence in one or more of the following: extraordinary progress in research, excellence in teaching, or excellent performance as a first-year graduate student. The executive officer for mathematics, in consultation with the faculty, determines the recipients. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

Scott Russell Johnson Graduate Dissertation Prize in Mathematics
A prize is awarded for the best graduate dissertation in mathematics. The prize may be split between two students. The executive officer for mathematics, in consultation with the faculty, selects the recipient. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

Abdul Kalam Prize in Aerospace Engineering
This prize is awarded to a student in the aerospace engineering master's program whose academic performance is exemplary and who shows high potential for future achievements.

John O. Ledyard Prize for Graduate Research in Social Science
The prize rewards the best third- year paper by a graduate student in Social Science or Behavioral Neuroscience. The prize is funded by Susan G. Davis in recognition of John O. Ledyard's dedication to developing graduate students as independent researchers and his service to the Division of the Humanities and Social Sciences. The prize is awarded annually by a committee of social science faculty.

The Herbert Newby McCoy Award
To support her husband's life-long interest in science, Mrs. McCoy designated that this annual award be made to a student or faculty member in the chemistry department of the California Institute of Technology making the greatest contribution of the year to science. The selection of the winner of this award shall be made by full professors of the Chemistry Department and the President of the California Institute of Technology.

Eleanor Searle Prize in Law, Politics, and Institutions
The Eleanor Searle Prize was established in 1999 by friends and colleagues to honor Eleanor Searle. The prize is awarded annually to an undergraduate or graduate student whose work in history or the social sciences exemplifies Eleanor Searle's interests in the use of power, government, and law.

Ernest E. Sechler Memorial Award in Aeronautics
An award is made annually to an aeronautics student who has made the most significant contribution to the teaching and research efforts

of the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT), with preference given to students working in structural mechanics.

The Ernest E. Sechler Memorial Award in Aeronautics was established in 1980 in memory of Ernest E. Sechler, who was one of the first graduates of GALCIT and who then served as a GALCIT faculty member for 46 years. Throughout his career, Sechler was the faculty adviser for aeronautics students. In addition, he made many contributions to structural mechanics in areas ranging from aeronautics to the utilization of energy resources.

John Stager Stemple Memorial Prize in Physics
A prize is awarded annually to a graduate student in physics for outstanding progress in research as demonstrated by an excellent performance on the oral Ph.D. candidacy exam. John S. Stemple was a Caltech physics graduate student when he died; a memorial fund was established from contributions made by the community of Falls Church, Virginia, John's hometown.

Charles Wilts Prize
The Charles Wilts Prize is awarded annually for outstanding independent research in Electrical Engineering leading to a Ph. Degree. This prize was established in 1992 to honor Charles Wilts, a member of the Electrical Engineering faculty from 1947–1975, who made substantial contributions to the Department of Electrical Engineering.

Note: Prizes and awards may be subject to federal and state income tax.

SPECIAL REGULATIONS OF GRADUATE OPTIONS

Aerospace

Aims and Scope of the Graduate Program
The Institute offers graduate programs in aerospace leading to the degrees of Master of Science in Aeronautics and Space Engineering, and Doctor of Philosophy in Aeronautics and Space Engineering The programs are designed to provide intense education in the foundations of the aeronautical and space sciences, with emphasis on research and analytical, computational, and experimental methods. Entering graduate students should have a thorough background in undergraduate mathematics, physics, and engineering science. Applicants for graduate study are also required to submit Graduate Record Examination scores with their applications.

In working toward a degree in aerospace, a student may pursue major study in one of the following areas: physics of fluids, physics of solids and mechanics of materials, structural mechanics, space technology, computational solid mechanics, computational and theoretical fluid dynamics, aeronautical engineering and propulsion, biomechanics of fluids and solids, technical fluid mechanics, control of aerospace systems and materials.

While research and course work in the aerospace option at the Institute cover a very broad range of subjects, a choice of one of the above fields allows students to focus their activities while taking advantage of the flexibility offered by the breadth of interests of the Graduate Aerospace Laboratories (GALCIT). A student with an interest in energy-related subjects will find many suitable courses and research projects of particular use. Subjects of major importance in the efficient use of energy, such as turbulent mixing, drag reduction, and flexible lightweight structures, have historically been the focus of research activity in the aerospace department.

In consultation with his or her adviser, a student will design a program of study in one of the above fields, consisting of the fundamental courses prescribed in the regulations for the separate degrees listed below, and of electives selected from the list of aerospace-related courses. The graduating student will be well-qualified for a career in aerospace and related fields.

Examinations, Committees, and Student Responsibilities

To help the student achieve satisfactory progress in his or her academic pursuits, the aerospace faculty provides for the following committee and individual support.

Upon beginning the first year of the aerospace program, each student is assigned a faculty (course) adviser whose research field matches the interests of the student as described in the student's statement of purpose in his or her admissions application. Students wishing to pursue studies leading to the Ph.D. must select and be accepted by a research adviser by the end of the spring term of the first year of residence and are required to pass a qualifying examination in the first term of the second year. Having passed the qualifying examination, the student pursues research under the supervision of the research adviser until he or she is ready to enter candidacy for the Ph.D. At this point, a four-member Candidacy Examination Committee that includes the student's research adviser is assembled and administers a Candidacy Examination to ensure the student has the appropriate knowledge and tools to successfully complete his or her chosen research activities.

The Candidacy Committee is chaired by a faculty member other than the research adviser. The Candidacy Examination should be administered by the start of the second term of the third year of residence but in any case must be successfully completed by the end of that year in order to comply with Institute requirements.

Conferral of the Ph.D. degree is contingent on satisfactorily passing the thesis examination before a committee consisting of four examiners, which may, but does not need to, have the same constitution as the Candidacy Committee.

Students may find further information concerning special option requirements and the requisite option forms on the GALCIT website.

Degree Programs in Aerospace

Master's Degree in Aeronautics and Master's Degree in Space Engineering

The master's degree program in aeronautics or space engineering is a one-year program that provides advanced training in the areas of aeronautics or space engineering beyond that covered in a four-year undergraduate program. The program consists of a set of five core courses (see details below). There is no research requirement, nor is a thesis required to obtain the degree. The courses required for the master's degree must be completed in one year.

Admission. Students whose highest qualification is a baccalaureate degree equivalent to that given by the Institute are eligible to seek admission to work toward the master's degree. Students are asked to submit course transcripts and letters of recommendation as well as GRE scores and evidence of English language proficiency as detailed in the graduate application. It should be noted that the graduate program at GALCIT is primarily focused on Ph.D.-level research and so priority in admission is given to those who plan to ultimately perform Ph.D.-level research.

*Course Requirements.*A program of study consists of courses totaling at least 138 units; of these, at least 84 units must be in the following subject areas:

- Fluid mechanics: 27 units (Ae/APh/CE/ME 101 abc)
- Solid/structural mechanics: 27 units (Ae/AM/CE/ME 102 abc)
- Mathematics or applied mathematics: 27 units (ACM 100 ab, ACM 104, or higher)
- Aerospace engineering seminar: 3 units (Ae 150 abc)

An additional 27 units are required as follows:

- a course in experimental techniques and laboratory work (Ae/APh 104 abc) for the master's degree in aeronautics, or
- a course in space engineering (Ae 105 abc) for the master's degree in space engineering.

A grade of C or higher must be nominally achieved in all the required classes unless they are only offered pass/fail, in which case a pass must be achieved in each class. For both the aeronautics and space engineering master's degrees, the remaining 27 units of electives are to be chosen from courses at Caltech that support the broader goals of the respective programs, subject to the approval of the option representative. Students must have a proposed program approved by their adviser prior to registration for the first term of work toward the degree.

Admission to More Advanced Degrees

Students who successfully complete the requirements for the master's degree and who wish to pursue the more advanced degrees of or Ph.D. must file a petition to continue work toward the desired degree. All students working for the Ph.D. degree are expected to register for and attend the advanced seminar (Ae 208 abc).

Degree of Doctor of Philosophy

Admission. Students with a baccalaureate degree equivalent to that given by the Institute are eligible to seek admission to work toward the degree of doctor of philosophy (Ph.D.) in aeronautics or space engineering. Students are asked to submit course transcripts and letters of recommendation as well as GRE scores and evidence of English language proficiency as detailed in the graduate application.

Course Requirements. The course requirements for the first year of the Ph.D. degree are identical to those of the master's degree. Students admitted to graduate study for the Ph.D. degree must, without exception, complete in their first year a course of study that would qualify them for the master's degree described above. The student may elect to receive the master's degree at the end of their first year after completion of these courses. However, a student who enters the Institute holding a master's degree from another institution will not normally be awarded a second master's degree in the same field.

Research adviser. Students wishing to pursue studies leading to the Ph.D. must select and be accepted by a research adviser by the end of their first year of study and prior to taking the qualifying examination described below.

Qualifying Examination. After the first year of graduate study, the student must pass a qualifying examination. The objective of the qualifying examination is to determine if the student is properly prepared and qualified to pursue problems typical of Ph.D.-level research. The exam will cover the following subjects:

- Fluid mechanics (Ae/APh/CE/ME 101 abc)
- Solid mechanics (Ae/AM/CE/ME 102 abc)
- Mathematics (ACM 100 ab, ACM 104)

The material covered in these examinations is at the same general level and breadth as covered in the corresponding first-year courses. The examinations are typically offered during one week in the first half of the fall term, in the second year of graduate residence at the Institute.

A student is examined orally on all three of these topics. In the event of an unsatisfactory performance, the examining faculty members may permit a repeat examination in the appropriate topics. The repeat examination must be scheduled prior to finals week of the winter term and must be completed before the end of the spring term of the same year.

Candidacy. To be recommended for candidacy for the Ph.D. in aerospace, the applicant must

- have satisfactorily completed at least 138 units of graduate work equivalent to the above Master of Science program;
- pass, with a grade of C or better, 27 units of graduate-level ACM courses beyond ACM 95/100, and ACM 104;
- complete (with a grade of C or better, or Pass) at least 45 units of aerospace courses numbered Ae 200 or higher, or Ae/ME 118, Ae/ME 120, EE/Ae 157, Ae 159, Ae/Ge/ME

160 and Ae/CE 165ab, excluding research and seminars; and
- complete three units of an advanced seminar such as Ae 208.

A proposed program conforming to the above regulations must be approved by the student's adviser and the option representative prior to add day of the first term of work toward the degree.

In addition to fulfilling these course requirements, the applicant must pass a candidacy examination in the third year of residence at the Institute. This exam should be administered by the start of the second quarter of the third year of residency. This examination aims at determining whether the student is successful in integrating formal course work into a mature understanding of fundamental engineering concepts, and at demonstrating his or her professional competence in applying these concepts to the problems being addressed in the course of their Ph.D. research.

Minor. No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

Foreign Languages. The student is encouraged to discuss with his or her adviser the desirability of studying foreign languages, but there is no formal foreign language requirement for the Ph.D.

Thesis and Final Examination. Before graduation, each candidate is required to give a public seminar presenting the results of his or her thesis research. For final examination and thesis completion, see also the general degree requirements and the section on Examinations, Committees, and Student Responsibilities regarding aerospace starting on page 320. A description of the requirements for conferal of a Ph.D. are given in section 4.

Subject Minor

A student majoring in a field other than aerospace may, with the approval of the option representative, elect aerospace as a subject minor. A minimum of 54 units in subjects acceptable to the aerospace faculty is required.

Problem and Grievance Resolution within Aerospace

Students may pursue several avenues for redress concerning personal and academic problems that may arise during their residency, as outlined by the Student Problem Resolution Process described earlier in the catalog. Should a student not wish to discuss the relevant issues with their adviser, the option representative and/or the director are always available to meet with the student. In addition, two other resources are available, one at the student and one at the faculty level. The student representative is elected annually by the aerospace graduate students at or after the Information Session, which is part of Ae 150. In the event that the student representative has completed his or her Ph.D. studies before the election date and left the Institute, the student organizer for Ae 150 may be his or her replacement. A faculty member chosen by the aerospace faculty to provide support for the students is available for student contact. The names of the current student and faculty support persons are available in the aerospace office.

Educational Exchange Program with Ecole Polytechnique
An educational exchange program is offered by the Aerospace option with Ecole Polytechnique (EP). In this exchange program, students selected for participation from Caltech will enroll for one year at EP. Correspondingly, students selected for the program from EP will enroll for one year at Caltech. To be eligible to participate, Aerospace students must have completed one full year of study (for Caltech students this is equivalent to the requirements for the MS degree) and agree that they will spend one full year at EP. First year (G1) graduate students enrolled in Caltech's doctoral aerospace program will be apprised of the opportunity to participate in an educational exchange program at the masters level at EP. A maximum of two student(s) will be selected by the Aerospace faculty from the pool of students who express interest in this program. Caltech students will follow their first (master's) year at Caltech, and their second year in the second year masters (M2) program at EP. For details of EP's program consult their web pages at http://www.mecanique.polytechnique.edu/home/programs-catalogue/master-mecanique-presentation-78056.kjsp

Caltech students must fulfill the requirements of their first year program and receive their Caltech MS diploma prior to proceeding to EP. Caltech students must register at Caltech during the year spent at Ecole Polytechnique and enroll in the special course Ae 240 – Educational exchange at Ecole Polytechnique. This ensures that they maintain their standing as enrolled graduate students at Caltech. It is implied that classes taken at one institution cannot duplicate classes already taken at the other institution. The expectation is that Caltech students will return to Caltech after completing the EP program and continue with their doctoral studies at Caltech. Caltech students should be prepared to take the qualifying exams in the fall term when they return from EP. Caltech students participating in the Caltech/EP educational exchange program will be considered to be on detached duty from Caltech while at EP. A detached duty agreement will be executed for each student that spells out the terms and requirements for the detached duty.

Applied and Computational Mathematics

Aims and Scope of the Graduate Program
Caltech's Computing & Mathematical Sciences department offers an interdisciplinary program of graduate study in applied and computational mathematics leading to the Ph.D. degree. This program is designed to give students a thorough training in fundamental computational and applied mathematics and to develop their research ability in a specific application field. The fields of application include

a wide range of areas such as fluid mechanics, materials science, and mathematical biology, engineering applications, image processing, and mathematical finance. The training essential for future careers in applied mathematics in academia, national laboratories, or in industry is provided by completion of the requirements for a Ph.D. degree in applied and computational mathematics.

The research areas and interests of the applied and computational mathematics faculty cover a broad spectrum, including nonlinear dynamics, computational biology, numerical analysis and scientific computing, computational and theoretical fluid mechanics, theoretical materials science, multiscale computations and homogenization theory, computational methods for electromagnetics and acoustics, statistics, signal and image processing, probability theory and stochastic analysis, and dynamical systems and geometric mechanics. As reflected by the faculty research activities, there is a strong emphasis on computational methods for solving challenging problems arising from engineering and scientific applications.

Reflecting the interdisciplinary nature of the program, several different groups, in addition to the applied and computational mathematics faculty, contribute to the teaching and supervision of research. Students in applied and computational mathematics are expected to combine their basic mathematical studies with deep involvement in some field of application. Basic general courses are listed specifically under applied and computational mathematics, and these are to be supplemented, according to the student's interest, from the whole range of Institute courses in specific areas of physics, biology, engineering, etc.

A regular colloquium provides the opportunity for visitors, faculty, and students to discuss current research.

Admission. Each new graduate student admitted to work for the Ph.D. in applied and computational mathematics is given an informal interview on Thursday or Friday of the week preceding the beginning of instruction for the fall term. The purpose of this interview is to ascertain the preparation of the student and assist him or her in mapping out a course of study. The work of the student during the first year will usually include some independent reading and/or research.

Course Requirements. All ACM students are required to take a total of 18 nine-unit courses at the graduate level (or the equivalent of 162 units) during their graduate study at Caltech. Among these 18 courses, the following core courses, typically taken during the student's first year of study, are required: ACM 101 ab, CMS/ACM 104, ACM 105, Ma 108 abc ACM 106 ab, CMS/ACM 116, and an application elective course. The application elective course in the first year is selected, with the recommendation of the student's adviser, from among a wide range of courses offered by an outside option within the Institute. In the second and third years, students are expected to take graduate-level courses appropriate to their chosen research area. The remaining courses towards the 162 unit requirement would normally include graduate-level ACM or CMS courses such as CMS/ACM

113, 201 ab, 210 ab, 216, 217, CDS 140, etc., as deemed appropriate to the student's research program, and which must be selected in consultation with the student's research adviser.

Students who have already taken some of the required courses may use them to satisfy the course requirements, even though the units may not be used to satisfy the total unit requirement for the Ph.D. degree. In addition, the student is required to enroll in CMS 290 for each quarter that he or she is in residence.

Master's Degree

Students are not admitted to work toward the master's degree. The master's degree may be awarded to an ACM student only in exceptional circumstances. Of the 135 units of graduate work required by Institute regulations, at least 81 units of advanced graduate work should be in applied mathematics.

Degree of Doctor of Philosophy

The Candidacy Examination. In order to be recommended for candidacy, the student must, in addition to satisfying the general Institute requirements, pass an oral or written candidacy examination administered by a faculty committee. This examination is offered during one week at the end of the first year of graduate residence at the Institute, typically near the beginning of the fall term. The material covered in this examination is based on the three core sequences described above. For students who have already taken the required courses before coming to Caltech, the examination can also be based on the substituted courses taken in the first year.

Advising and Thesis Supervision. Upon passing the candidacy examination (usually by the end of the second year), the student is required to choose a thesis supervisor who assumes the major responsibility in supervising the Ph.D. thesis. At the same time, an advising committee consisting of three faculty members is formed to help oversee the advising process. This committee should be formed no later than the third year of graduate study. The student's supervisor is part of this committee, but does not chair the committee. The student is encouraged to meet with the committee members informally for advice or suggestions. Joint supervision between two faculty members is also possible, as is seeking a thesis adviser outside the core applied and computational mathematics option, although in this case it is mandatory that an applied mathematics faculty member be nominated as a co-adviser.

Should a disagreement of any kind occur between the student and his or her supervisor as regards the timely completion of the thesis, the student is encouraged to direct his or her concerns to the committee chair. If this is not workable, the student should feel free to consult with the option representative, the executive officer, or an applied and computational mathematics faculty member of the student's choice. If the student's concerns cannot be resolved through consultation with these individuals, the student is encouraged to pursue resolution of his or her concerns through other channels as outlined in Student Problem Resolution Process on page 50.

Submission of Thesis. On or before the first Monday in April of the year in which the degree is to be conferred, a candidate for the degree of Ph.D. in applied and computational mathematics must deliver a typewritten or printed copy of the completed thesis to his or her research supervisor.

Final Examination. The final oral examination is held within four weeks after the submission of the thesis. The examination covers the thesis and related areas.

Subject Minor in Applied and Computational Mathematics

The group of courses must differ markedly from the major subject of study, and must include 54 units of advanced courses in applied mathematics and must not be simultaneously used for fulfilling a requirement of the second option. The qualifying courses exclude ACM95/100, although some flexibility is allowed depending upon the option of origin. The student must pass an oral examination whose subject is directly related to the material covered in the qualifying courses. This oral examination will be waived if the student has received a grade of A in every course.

Applied Mechanics

Aim and Scope of the Graduate Program

Applied Mechanics (AM) research and study are offered through the Department of Mechanical and Civil Engineering (MCE). The degrees of Doctor of Philosophy (Ph.D.) and Master of Science (M.S.) are offered. The M.S. degree is normally only awarded to students who expect to pursue the Ph.D. degree in applied mechanics and who do not already have an M.S. degree in applied mechanics. In general, students who intend to work full-time toward the Ph.D. degree as a final degree objective are admitted to the applied mechanics graduate program.

The aim of the graduate program in applied mechanics at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, with a strong background in the basic and engineering sciences. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Preparation for the Graduate Program

Students who have not specialized in applied mechanics as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may provide a suitable background as well. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty.

Master's Degree Description and Requirements
The degree of Master of Science in applied mechanics is only awarded to students who do not already have an M.S. degree in applied mechanics. The degree will be awarded upon request by students who have fulfilled the requirements. Only in exceptional cases is there admission to the M.S. program as the final degree objective.

A minimum of 138 units of courses numbered 100 or above, that meet the required master's program listed below, must be passed with a grade of at least C for completion of the master's degree in applied mechanics. All units must be taken for grades, except for courses offered only on a pass/fail basis. The M.S. degree in applied mechanics is typically completed within the first two years of residency at Caltech.

Each student's program must be approved by the adviser and option representative in mechanical and civil engineering before registering for the course.

Required Master's Program

a) Graduate applied mechanics core (45 units). These units should provide a solid base for the student's engineering interest. The courses should be selected from the core subjects list Areas 1-3 of the applied mechanics Degree of Doctor of Philosophy Description and Requirements section.
b) Mathematics, engineering, and research electives (63 units). Students who have not taken the equivalent of ACM 100 ab are required to take ACM 100 ab for 24 units. Research up to a maximum of 27 units.
c) Free electives (27 units). These units may be selected from any course with a number of 100 or greater, except that research units may not be included.
d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

Degree of Doctor of Philosophy Description and Requirements
The Ph.D. degree in applied mechanics is focused on research. Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project resulting in an original contribution to the field which is documented by a thesis is required. Institute requirements for the Ph.D. degree are described in the section on degree requirements. A minimum of three academic years in residence as a graduate student are required by the Institute, and two or more additional years are usually needed for preparation of the thesis.

Advising and Thesis Supervision. An interim adviser is appointed for each student upon admission to a graduate degree in applied mechanics. The interim adviser will serve as the primary mentor until the student finds a research adviser. It is the responsibility of the student to find an academic and research adviser within three terms of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee within four terms of graduate residence at Caltech. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering. The committee shall meet as requested by the student. Further, the committee shall meet annually to review progress and to approve the registration of the student beyond the fifth year of graduate residence at Caltech.

The adviser and the thesis advisory committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in applied mechanics, the student must, in addition to meeting the general Institute requirements, do the following:

- Obtain the agreement of a professorial faculty member to serve as his or her academic and research adviser before the end of the third term of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee before the end of the fourth term. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering.
- Pass both subject and research components of the oral candidacy examination before the end of the eighth term of graduate academic residence at Caltech. If the student has chosen a subject minor, an examinationon the subject of that program may be included at the request of the discipline offering the subject minor.
- Complete a minimum of 195 units of courses numbered 101 or above, that meet the required Ph.D. program listed below. All units must be taken for grades and passed with a grade of at least a C, except for courses offered only on a pass/fail basis. The course work towards the Ph.D. degree in applied mechanics is typically completed within the first three years of residency at Caltech.

Required Ph.D. Program.

a) Applied Mechanics core subjects (45 units). Course work in a minimum of two core applied mechanics subjects, minimum of

18 units each of two subjects, spanning at least two broad areas listed below. Most students prepare for the subject candidacy exam by taking the recommended set of courses listed below in Areas 1-3, plus math. These units may also be used in the student's program for the master's degree. Examples of suitable courses are given in parentheses.

Core AM Subjects
Area 1
Fluid Mechanics (Ae/APh/CE/ME 101 abc)
Mechanics of Structures and Solids (Ae/AM/CE/ME 102 abc)

Area 2
Dynamics & Vibrations (AM/CE 151 ab)

Area 3
Structural & Earthquake Engineering (CE 160 ab)
Seismology (CE 181 ab, Ge 162)

The student may petition the mechanical and civil engineering option representative to accept alternate subjects or areas. These changes should retain core applied mechanics knowledge, should not be a sub-specialty of one of the listed areas, and should represent sufficient breadth. The approval is not automatic; such petitions are submitted rarely and many have been denied in the past. The petition must be submitted to the option representative and approved before the student registers for the course.

b) Additional engineering or science courses, with a course number 101 or above (63 units). Pass with a grade of at least C, courses that pertain to the student's specialty and are approved by the thesis advisory committee.
c) Advanced mathematics or applied mathematics (27 units). Pass with a grade of at least C, chosen in consultation with the adviser from the following list: ACM 101 or higher, CDS 140, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.
d) Graduate engineering seminar (6 units). Pass six terms of AM/CE/ME 150 abc, within twelve terms, 3 years, in residence at Caltech.
e) Research (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

The requirement of a minimum grade of C will be waived for an advanced course which is offered only pass/fail. The faculty will evaluate the student's research progress, class performance, adviser's input, and oral candidacy exam results to determine whether a student will be admitted to, or be able to maintain candidacy for, the Ph.D. degree.

Registration Beyond the Sixth Year of Graduate Residence. The annual approval of the Ph.D. dissertation supervision committee is necessary for registration beyond the twenty-fourth academic term of graduate residence at Caltech.

Thesis and Final Examination. The thesis examination will be given after the thesis has been formally completed. This examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. The format of the examination can be chosen from the following two options, by the student, in consultation with their research advisor: (i) a public seminar presented by the candidate, with an open question period, followed by a private examination by the examining committee or (ii) a private presentation to the examining committee followed by the examination, with a public seminar on another date. The examining committee shall consist of a minimum of four voting members, three of whom must be Caltech faculty; two members must be from MCE. The thesis defense committee shall be chaired by a committee member who is an MCE Caltech professorial faculty member and not the student's adviser.

Subject Minor

A student majoring in another branch of engineering or another division of the Institute may, with the approval of the faculty in the department of mechanical and civil engineering and the faculty in his or her major field, elect applied mechanics as a subject minor. The program of courses must differ markedly from the major subject of study or research, and must consist of at least 54 units of advanced courses (101 or above) approved by the faculty in mechanical and civil engineering.

Applied Physics

Aims and Scope of the Graduate Program

Applied Physics is a broad field of study that lies at the intersection of physics and many other fields of science and engineering. The Applied Physics Option at Caltech is accordingly a highly multi-disciplinary program that is designed to train students in a broad spectrum of physics and engineering fields at an advanced level. Moreover, it is our goal to cultivate abilities in our graduates to apply this knowledge throughout their lives so as to make technological and scientific breakthroughs at the edge of current knowledge.

Preparation for the Graduate Program

Students admitted for graduate study can enter from a broad range of disciplines, but are expected to have a rigorous background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may provide a suitable background as well. The qualifications of each applicant will be considered individually. After enrollment, the student will arrange a course of study and research in consultation with members of the faculty and the Applied Physics option representative.

Description of the Degree of Doctor of Philosophy (Ph.D.)
To receive the doctoral degree in Applied Physics students must demonstrate the ability to formulate and execute an original program of scientific study. As part of this, a doctoral candidate is expected to develop a deep understanding in a chosen field of specialization; to develop tools with which to assess problems outside one's field of specialization; to develop rigor and strength in the physical sciences for self-education beyond formal training; and to develop skills to become a productive member of the community of scholars. All students wishing to enter the program must complete a series of preparatory courses, followed by an oral candidacy exam in which the student describes their proposed topic of research and is examined on their knowledge of course subject matter. Upon passing the candidacy examination, students work towards completion of a thesis in consultation with their research advisor. The doctoral degree is awarded upon approval of a written thesis by a faculty committee, and successful defense of the thesis in a final oral examination. There is no separate Master's Program in Applied Physics. However, with the approval of the student's advisor and the Applied Physics option representative the degree of Master of Science in Applied Physics may be awarded after the fulfillment of the course requirements described below.

Advising and Thesis Supervision
An interim adviser is appointed for each student upon admission to the graduate program in Applied Physics. Typically, this person is the Applied Physics option representative. In consultation with the interim adviser the student will determine a course schedule and identify a faculty research advisor. This most often occurs within the first year of graduate residence. The faculty advisor is the student's primary mentor and the student will work in the advisor's research group to formulate and execute a plan of study leading to the thesis. In consultation with their research adviser, the student will also form a Ph.D. thesis advisory committee. This four-member committee should include the student's advisor and at least three members of the Caltech professorial faculty from either the Applied Physics or Physics options. The thesis advisory committee will conduct the qualifying examination and also approve the thesis and conduct the thesis defense. The membership of this committee may change between the time of the qualifying exam and the final defense.

Requirements for Candidacy to the Ph.D. Degree
To be recommended for candidacy for the Ph.D. degree in Applied Physics, a student must demonstrate mastery in the following five areas of pure and applied physics:

- Classical Physics: Mechanics and Electromagnetism
- Quantum Mechanics
- Mathematical Methods
- Statistical Physics and Thermodynamics
- Biophysics, Optical Physics, Hydrodynamics, Plasma Physics, or Solid State Physics

A. Graduate Coursework towards Candidacy

In partial fulfillment of the "mastery" requirement a student must successfully complete a minimum of 135 units of courses numbered 101 or above from the course schedule. In addition, 4 units of APh 110ab must also be completed. All courses must be passed with a grade of at least a C, except for courses offered only on a pass/fail basis. Moreover, no more than 27 units of APh 200 units may be counted towards the 135 unit requirement of candidacy. Students must also complete the degree progress report online upon completion of their courses.

	Total Units
1. Classical Mechanics and Electromagnetism	**27**
Topics in Classical Physics	
Ph 106a (9 units)	
Ph 106b (9 units)	
Ph 106c (9 units)	
2. Quantum Mechanics	**27**
Ph – Quantum Mechanics	
Ch – Elements of Quantum Chemistry	
Ph 125a/Ch 125a (9 units)	
Ph 125b/Ch 125b (9 units)	
Ph 125c/Ch 125c (9 units)	
3. Mathematical Methods	**27–33**
ACM – Methods of Applied Math	
Ph – Mathematical Methods of Physics	
ACM 101a/Ph 129a (12/9 units)	
ACM 101b/Ph 129b (12/9 units)	
Ph 129c (9 units)	
4. Statistical Physics and Thermodynamics	**27**
APh – States of Matter	
Ph – Statistical Physics	
APh 105a/Ph 127a (9 units)	
APh 105b/Ph 127b (9 units)	
APh 105c/Ph 127c (9 units)	

5. One of the following course sequences in Biophysics, Optical Physics, Hydrodynamics, Plasma Physics, or Solid State Physics:

(It is recommended that students complete one full sequence from the courses listed below (i.e. every term of a single course. Exceptions may be made after consultation with the option representative.)

Fluid Mechanics	**27**
Ae/APh/CE/ME 101a (9 units)	
Ae/APh/CE/ME 101b (9 units)	
Ae/APh/CE/ME 101c (9 units)	

Solid-State Physics	**27**
APh 114a (9 units)	
APh 114b (9 units)	
APh 114c (9 units)	
Physics of Momentum Transport in Hydrodynamic Systems	**24**
APh/Ph 115 (12 units)	
APh/Ph 116 (12 units)	
Plasma Physics	**27**
APh 156a (9 units)	
APh 156b (9 units)	
APh 156c (9 units)	
Physical Biology of the Cell, Physical Biology Lab	**24**
APh/BE 161 (12 units)	
APh/BE 162 (12 units)	
Electromagnetic Theory, Light Interaction with Atomic Systems – Lasers, Special Topics in Photonics and Optoelectronics	**27**
APh 130 (9 units)	
APh 131 (9 units)	
APh 132 (9 units)	
Physics of Semiconductors and Semiconductor Devices	**27**
APh 183a (9 units)	
APh 183b (9 units)	
APh 183c (9 units)	
Quantum Electronics	**27**
APh 190a (9 units)	
APh 190b (9 units)	
APh 190c (9 units)	

First year students are also required to take APh 110ab, a two term seminar course in which faculty review their research areas and ongoing research work in their group.

	Total Units
Faculty Presentation Seminar for 1st Year Graduate Students	**4**
Topics in Applied Physics - Weekly Faculty Seminars	
APh 110a (2 units)	
APh 110b (2 units)	

In addition to work in the classroom, students must complete a minimum of 27 units of laboratory or reading research through APh 200.

Applied Physics Research

	Total Units
APh 200	27

Students entering the program with advanced preparation may choose either to substitute more advanced courses in the topical areas shown or to demonstrate competency by successfully passing both the midterm and final examinations. In such cases, students may petition the Applied Physics option representative to accept alternate subjects or areas. These changes should retain core applied physics knowledge, and maintain sufficient breadth. All such petitions must be submitted to the option representative and approved before the student registers for the course.

Coursework towards the Ph.D. degree in Applied Physics is normally completed within the first two years of graduate residency.

B. Candidacy Examination.
To fulfill the requirements for candidacy all students must pass an oral examination after completing their coursework. This examination must be taken before the beginning of the student's third year in residence. Students will be expected to deliver a half-hour oral presentation giving a prospectus on their proposed thesis research. Following questions on the research prospectus, a more open-ended set of questions will be posed to the student by the committee members to test general proficiency in the five areas of pure and applied physics listed above. Students who fail the oral examination on their first attempt will be given additional guidelines for further study and an opportunity to retake the examination a second and final time if the committee so recommends. Should a student fail the oral examination a second time, he/she cannot continue with doctoral studies leading to the Ph.D. Upon recommendation of the examining committee, however, the student may be granted a Master's degree. Annual approval of the Applied Physics option representative is necessary for registration beyond the third year of graduate residence if the student has not completed the candidacy examination.

Students who fulfill the requirements above will be recommended for candidacy to the doctoral program and a master's degree (if applicable) in applied physics.

Ph.D. Thesis Requirements
The candidate is to provide a draft copy of his or her completed thesis to the members of the examining committee (typically the same as the thesis committee) at least two weeks before the final oral examination. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until

the thesis is submitted in completed form, i.e., ready for review by the dean, the members of the thesis committee, and the Graduate Office proofreader. Registration is required for the term in which the thesis defense is taken, but is not normally allowed beyond the last date of the term. For more information, please see the section entitled "Information for Graduate Students" in the Caltech catalog.

Ph.D. Final Examination
The candidate shall undergo a final broad oral examination (thesis defense) in the field, to include the subspecialty represented by the thesis and the significance of its findings to the field. This oral examination will be administered at least two weeks after the doctoral thesis has been presented in final form so that the examining committee has sufficient time to review its content. This examination must be taken at least three weeks prior to the date on which the degree will be officially conferred.

Registration beyond the Sixth Year of Graduate Residence
The annual approval of the student's thesis advisory committee is necessary for registration beyond the twentieth academic term of graduate residence at Caltech.

Subject Minor
Graduate students majoring in other fields may elect a minor in Applied Physics. In addition to general Institute requirements, the student must complete, with a grade of C or higher, 81 units of courses in applied physics above the 100 level, excluding APh 200. The minor is also subject to the following conditions:

- Students cannot use courses required by their major option in fulfillment of this requirement.
- Students interested in a minor must receive prior approval from the option representative in Applied Physics, who will review and approve the proposed course of study.
- It is recommended that this course of study include advanced courses spanning different subfields of Applied Physics.

Astrophysics

Aims and Scope of the Graduate Program
With the goal of understanding the physical processes that govern the universe, its constituents, and their evolution, astronomy uses the apparatus and methodology of physics to gather and interpret data. Major activities of astrophysics are the development of new technologies for astronomical research, and theoretical prediction and simulation of cosmic phenomena using the laws of physics.

The primary aim of the graduate astrophysics program at Caltech is to prepare students for creative and productive careers in astrophysical research and a variety of other challenging vocations. The astrophysics program emphasizes independent research by graduate students, who are free to pursue study in virtually any area of astrophysics. The opportunity exists to take advantage of the many observational facilities owned and operated by Caltech (see page 118).

Admission. Incoming students should have a strong background in physics, and although a good preparation in astronomy is helpful, this is not required for admission to the graduate program. All applicants, including those from foreign countries, are requested to submit Graduate Record Examination scores for verbal and quantitative aptitude tests and the advanced test in physics.

Master's Degree

While the option does not offer a master's degree program in itself, students who fulfill the general Institute requirements for such a degree, and the specific option requirements (see below), can receive a master's degree, either en route to a final Ph.D. degree if admitted to candidacy, or as a terminal degree if the candidacy requirements are not met.

The choice of astronomy and other science elective courses must be approved by the option representative. At least 36 units of the 135 units must be selected from Ay 121–127. The courses Ph 106, Ph 125, and Ph 129 may be required of those students whose previous training in some of these subjects proves to be insufficient. At least 27 units of advanced courses in fields other than astronomy are required.

Degree of Doctor of Philosophy

Astrophysics Program. The student's proposed overall program of study must be approved by the option representative during the first year. The following are required of all students for candidacy: Ay 121, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127. The student should take these courses in the first year. Students must also take at least one term of Ay 122 unless exempted. Also required are research and reading projects. Credit for this work will be given under courses Ay 142 and Ay 143. The above courses must be passed with a grade of B– or better.

Physics Program. The student's program during the first two years of graduate study should include at least 36 units of physics courses, exclusive of Ph 106, Ph 125, and Ph 129, and should include Ph 136 a and Ph 136 b, unless specifically exempted. Students in radio astronomy may substitute an advanced course in electrical engineering or applied mechanics for up to 9 of the required 36 units of physics, and students in planetary astronomy may similarly substitute an advanced course in geophysics or geochemistry for up to 9 of the required 36 units of physics. Cross-listed courses (e.g., Ph/Ay) in general do not count toward the physics units requirement, unless specifically allowed by prior consultation between the student, the instructor, and the option representative. This requirement may be reduced on written approval for students who take substantial numbers of units in Ph 106, Ph 125, and Ph 129. Theoretical astrophysics students should include at least 54 units of physics or applied mathematics courses in their programs. No more than 18 of the 36 units may be taken P/F; all others must be passed with a grade of C or better. In subsequent years,students are encouraged to take additional advanced astronomy courses, but there is no specific requirement, and they do not count towards the 36 units of physics.

Other Requirements. An ability to explain concepts and to verbally present one's work is vital to a successful career in research and/or teaching. To this end, all graduate students in astrophysics are required to serve as teaching assistants during their second year, and to make oral presentations as part of the course Ay 141, 3 terms of which must be taken every year by all students beginning in their second year.

The Minor. It is recommended that students take a subject minor in physics. Other fields in which subject minors are taken include geology or engineering, depending on the student's field of specialization.

Language Requirement. Although the department believes that knowledge of foreign languages is generally useful, there is no formal foreign-language requirement. However, graduate students for whom English is a second language may be required to demonstrate fluency in oral and written English at the time of their candidacy exam. The examining committee will administer a test when this is deemed necessary.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in astrophysics, a student must, in addition to meeting the general Institute requirements:

- complete satisfactorily 36 units of research (Ay 142) or reading (Ay 143);
- pass satisfactorily, or by special examination, the required astrophysics courses (see above);
- pass a general oral examination (see below);
- pass a thesis-related examination (see below);
- complete the physics course requirement (see above);
- satisfy a teaching requirement (generally two terms as a GTA);
- fulfill the language requirement if applicable (see above); and
- be accepted for thesis research by a member of the faculty.

In fall of their second year, all students are required to take a general oral qualifying examination. Students will be examined on the substance and status of, as well as their performance on, a research project, which should be started not later than the summer following the first year. They will further be examined on their broad understanding of current topics in, and fundamentals of, astrophysics. Both of these aspects of the examination are intended to evaluate the candidate's aptitude for a research career in astrophysics. In addition, at the discretion of the executive officer, students who have not done well in one, or at most two, areas covered in the Ay 120 course series during their first year will be retested in these areas during the examination. Students must pass all of the aspects of this examination, as judged by the faculty committee conducting it, in order to continue in the Ph.D. program.

Students who do not meet the minimum grade requirements in the Ay 121–127 series, or who do not pass the general candidacy examination described above, will not be able to continue in the Ph.D. program. They may receive a terminal master's degree, provided that they fulfill the requirements for it (see above).

Advising and Thesis Supervision. By the summer of their first year, students should be spending most of their time on research. During their first two years, students are free to work with any faculty they wish, on one or more projects. However, by the summer of their second year at the latest, they should have defined a thesis project and been accepted by a faculty research adviser for that project (in cases where the thesis involves multiple projects, a second faculty adviser may supervise part of the research, but one must be selected as primary adviser). An oral candidacy exam dealing with the student's proposed thesis research should be taken before the end of the third year. The date and time of the exam are the responsibility of the student to arrange. The examining committee is chosen by the executive officer in consultation with the student's adviser. It will stand until the final examination, and be charged with ensuring that satisfactory progress toward the Ph.D. is being made.

If the candidate does not pass the oral candidacy exam, then the examining committee may at its discretion offer the candidate a second oral examination. This examination must be successfully completed by the end of the third term of the third year.

After the oral candidacy exam, the adviser and the student together have primary responsibility for the student's progress and career development. To ensure that these remain on course, both student and adviser must submit annual progress reports to the executive officer (or in the case of a conflict of interest, to the astrophysics option representative or the division chair). If at any stage the student, the adviser, or the executive officer feels that there are serious problems developing, they may consult in confidence with the astrophysics option representative, the executive officer, or the division chair. They may also request a meeting of the oral candidacy exam committee or seek the advice or help of other faculty members. Students may also seek confidential advice and help from the Counseling Center and the Ombuds Office.

Final Examination. A final draft of the thesis must be submitted at least six weeks before the commencement at which the degree is to be conferred. At least two weeks after submission of the thesis, the student will be examined orally on the scope of his or her thesis and its relation to current research in astrophysics. The examination will be conducted by a committee selected in the same way as the oral candidacy committee. The examination should occur before the end of the fifth year.

Typical Timeline

Year 1: Ay 121, Ay 123–127; at least two advanced physics courses; reading and independent study. Begin research.

Year 2: Early fall—general oral qualifying examination. Research projects; select thesis and adviser. Fulfill teaching requirement.

Complete 36 units of physics (54 for theorists); a term of Ay 122 if applicable; optional advanced astronomy courses. Ay 141.

Year 3: Take oral candidacy exam on thesis before end of second term. Annual report from student and adviser. Ay 141.

Optional Advanced Courses:

Year 4: Annual report from student and adviser. Ay 141.

Year 5: Annual report from student and adviser. Ay 141. Complete Ph.D. thesis before end of year 5. Final oral examination.

Subject Minor

The program for a subject minor in astrophysics must be approved by the department before admission to candidacy. In addition to general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in astronomy.

Behavioral and Social Neuroscience

Aims and Scope of the Graduate Program

Bioengineering research at Caltech focuses on the application of engineering principles to the design, analysis, construction, and manipulation of biological systems, and on the discovery and application of new engineering principles inspired by the properties of biological systems. Areas of research emphasis include: biodevices, bioimaging, bioinspired design, biomechanics, biomedical engineering, cell and tissue engineering, molecular programming, synthetic biology, and systems biology. The goal of the doctoral program is to prepare students to become leading scientists and engineers in academia and industry. The graduate program aims to educate students to be highly competent in their chosen area of research, but also provide them with a broad knowledge foundation in bioengineering. By graduation, students are expected to have a working knowledge of bioengineering in general and an in depth knowledge of their chosen area, have independently planned and conducted research experiments in their chosen area, and successfully defended their thesis work in an open forum.

Master's Degree

Students who are enrolled in the BSN Ph.D. program may earn a M.S. degree after successful completion of 36 units of course work, approved at least with a B grade, in addition to completing the coursework required for the first year of the Ph.D. program.

Admission. Admission to the Caltech Ph.D. program is based on prospective students' academic records, research interests, GRE scores, and letters of recommendation. Students who are not native English speakers are also required to submit scores from the TOEFL exam.

Course Program. First year. The first-year curriculum consists of: Analytical Foundations in Social Science (SS 201 abc), Econometrics (SS 222 abc), Behavioral and Social Neuroscience (CNS/SS/Psy/Bi

102 ab), Neurobiology (Bi/CNS 150), Computational Neuroscience (CNS/Bi/Ph/CS 187), and three lab rotations (with the third lab rotation completed during the summer). Each class must be completed with a grade of B or better. Students are also required to audit one quarter of an introductory social science class, either Introduction to Economics (Ec 11) or Introduction to Political Science (PS 12). Before the start of the second year, students are required to take a written preliminary examination which has two components, one corresponding to the SS201 sequence, and one for SS 222. The grades given are Honors, Pass, and Fail. Students must achieve at least a Pass in both exams. The social science faculty will review the student's performance on the exam, and progress, to date. If it is not satisfactory, they may terminate the student from the program by the beginning of the second year.

Second year. Students must complete one of the sequences SS 202 abc (Political Theory) or SS205abc (Foundations of Economics), and pass a preliminary examination in the chosen sequence at the end of the second year. During the spring quarter of the second year, students must enroll in SS 281 (Graduate Social Science Writing Seminar). Students enroll in SS 300 for the credits remaining to reach 36 per quarter. All classes offered for grades must be taken for grades, and completed with a grade of B or better.

Third year. Beginning in their third year, and in all subsequent years, all students should also enroll in the 3-unit graduate student seminar (SS 282) every quarter. Every student must make a presentation in this class at least once a year. Students should enroll in Research in Social Science (SS 300) for the units remaining to reach 36.

Fourth and fifth year. Students need to register for 33 units of SS 300 and 3 units of the graduate student seminar SS 282.

Progress in the program, and advancement to candidacy

In addition to the coursework and examinations described above, students must enroll in 36 units per quarter, and complete the following requirements.

By the end of the second year, students must submit a research paper, which may be co-authored, to the DGS. If their primary adviser, and the second member on their dissertation committee, find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will review the student's paper. If they decide that the paper is not satisfactory, they may terminate the student from the program.

Third-year students must write a research paper, which may be co-authored, and present it to the faculty by the end of the third quarter. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience.

After completion of the third-year paper presentation, the social science faculty evaluates the student's overall performance and research potential. This review is based primarily upon the third-year paper, but the faculty also verifies that the student has satisfactorily completed all previous requirements. If this evaluation is favorable, the student is admitted to candidacy for the Ph.D. If the faculty evaluation is unfavorable, the student may be terminated from the program.

Organization of the Thesis Committee. By the start of their second year, students should have selected a primary adviser and be assigned a lab. The adviser shall serve as chair of the student's dissertation committee, and must be a faculty member in behavioral and social neuroscience at Caltech. It is possible to change advisers if a student's research interests change. A second committee member, who should be a faculty member in either BSN or in social science, should be chosen by February 1 of the second year.

Students, in consultation with their advisers, must select one additional committee member after the student has advanced to candidacy (normally by the beginning of their fourth year). One member may be from outside the social science faculty; such choices must be approved by the DGS. After a student advances to candidacy, the division chairperson shall select a fourth member of the committee with an eye to representing the diverse interests of the social science faculty.

Degree of Doctor of Philosophy

By November 1 of their fourth year, students must complete a dissertation prospectus that outlines the proposed dissertation work, and presents a tentative schedule detailing when the components of the dissertation are to be completed. The prospectus must clearly identify a project, or dissertation components, that should culminate in a job market packet at the beginning of the students fifth year. The prospectus must be approved by the dissertation committee by November 1, and communicated by the principal adviser to the DGS.

By May 1 of the fourth year, all students are required to convene a thesis prospectus seminar with their adviser and other committee members. In this seminar, they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. Students and their committee should reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation.

After the dissertation has been completed, students, in consultation with their adviser, must schedule an oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research.

Biochemistry and Molecular Biophysics

Aims and Scope of the Graduate Program

An integrated approach to graduate study in biochemistry and molecular biophysics has been organized primarily by the Division of Biology and Biological Engineering and the Division of Chemistry and Chemical Engineering. The curriculum is designed to provide a broad background in biochemistry and biophysics of macromolecules and molecular assemblies, in addition to an appropriate depth of knowledge in the field selected for the Ph.D. thesis research.

Admission. The option in biochemistry and molecular biophysics is open to students with undergraduate degrees in biochemistry, biology, chemistry, biophysics, physics, engineering, and related areas. All applicants for admission, including those from foreign countries, are required to submit the verbal, quantitative, and analytical scores for the Graduate Record Examination and are also strongly urged to submit the results of an advanced test in a scientific field. Applicants whose native language is not English are required to submit results of the TOEFL exam and, after admission, are required to satisfy the English language requirements of the Institute.

Master's Degree

Students are not normally admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met. In general, the degree is not conferred until the end of the second year of residence.

Degree of Doctor of Philosophy

The Option Graduate Study Committee will counsel and oversee the student's progress upon admission to the graduate program. In the first year of graduate study, the course requirement consists of a sequence of three core courses covering the biochemistry and biophysics of macromolecules and molecular assemblies (BMB/Bi/Ch 170); biophysical and structural methods (BMB/Bi/Ch 173); and molecular machines (BMB/Bi/Ch 174). These courses will expose the student to contemporary issues in biochemistry and molecular biophysics, and to the tools and methods that are essential for research in this area. Research advisers are normally selected at the end of the first year. In consultation with their adviser, students are expected to take three additional advanced courses of nine or more units in the first and second years that are appropriate for their particular research interests.

Laboratory Rotations. In consultation with the Option Graduate Study Committee and individual professors, students will choose three laboratories in which to do short research projects during their first year of residence. These laboratory rotations are designed to provide the student with an introduction to different areas of biochemistry and molecular biophysics. It is possible to waive some or all of the rotations by petitioning the Option Graduate Study Committee.

Admission to Candidacy. By the end of the sixth term of residency, the student will take an oral examination to assess mastery of the field of biochemistry and to evaluate research progress. As part of this examination, each student will submit a written research report summarizing the progress in their research, and an original research proposition in a field outside the student's chosen field of research. A candidacy examination committee will be assembled by the Option Graduate Study Committee to administer the examination. When the student advances to candidacy upon successful completion of the exam, this committee will become the thesis advisory committee and will meet with the student once a year to evaluate research progress. This committee will also serve as the Ph.D. thesis examination committee.

Thesis and Final Examination. Thesis research will be carried out under the direction of one or more faculty members in the biochemistry and molecular biophysics option. The thesis defense will consist of a thesis seminar, followed by an examination by the Ph.D. thesis committee.

Bioengineering

Aims and Scope of the Graduate Program

Bioengineering research at Caltech focuses on the application of engineering principles to the design, analysis, construction, and manipulation of biological systems, and on the discovery and application of new engineering principles inspired by the properties of biological systems. Areas of research emphasis include: biodevices, bioimaging, bioinspired design, biomechanics, biomedical engineering, cell and tissue engineering, molecular programming, synthetic biology, and systems biology. The goal of the doctoral program is to prepare students to become leading scientists and engineers in academia and industry.

Master's Degree

Students are not admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met.

Degree of Doctor of Philosophy

In addition to satisfying the general Institute requirements, candidates for a Ph.D. in bioengineering at Caltech must satisfy the following requirements.

Course Requirements. Coursework requirements provide maximum flexibility in building on undergraduate training and complementing the research activities of each student. Students take six electives (one-quarter courses totaling at least 54 units; grade of B or higher in each course) selected in consultation with the student's advisor and the option representative. To maximize the opportunity for research during the early stages of the graduate career, coursework may be spread over the first and second years.

Examples of relevant electives include:

Bioimaging and biomedical devices electives
AM/CE 151 ab, APh 109, APh/EE 130, APh/EE 132, BE/EE/MedE 189 ab, Bi/BE 177, Bi/BE 227, ChE/BE 112, EE/APh 131, EE/BE/MedE 166, EE/BE/MedE 185, EE/MedE 187, Ph 106 abc, Ph/APh/EE/BE 118 abc.

Biomechanics and bioinspired design electives
Ae/APh/CE/ME 101 abc, Ae/AM/CE/ME 102 abc, Ae/BE 242, BE/Bi/MedE 106, BE 159, ChE 103 abc, ChE 151 ab, ChE/Ch 164, ChE 174, MedE/BE/Ae 243, Ph 127 abc.

Synthetic biology, systems biology, molecular programming, and cell and tissue engineering electives
BE 150, BE 153, BE 159, BE/APh 161, Bi 117, Bi 145ab, ChE/BE 163, BE/CS/CNS/Bi 191ab, ChE 130.

Biology electives
BE 150, Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi 114, Bi 115, Bi 117, Bi 118, Bi 122, Bi 129, Bi 145 ab, BE 153, BE 159, BE/APh 161, Bi/CNS 150.

Math electives
ACM 100 ab, ACM/EE 116, ACM/ESE 118, AM 125 abc, ChE 105, CDS 110, CDS 140.

To assist in the selection of a research area, to foster interactions within the entering class, and to discuss ethical guidelines for scientific research, first-year students participate in three discussion courses totaling 9 units: current research topics in Caltech bioengineering labs (BE 167; 1st term); reading the bioengineering literature (BE 168; 2nd term); responsible conduct of research (Bi 252; 3rd term).

Research. The flexibility of the coursework requirements enables research to be the primary activity from the very first term in residence. Students are encouraged to do two or more research rotations during the first year to sample research activities in multiple labs before selecting a Ph.D. adviser. Rotations are arranged by contacting individual faculty.

Adviser Selection. Each student must select a Ph.D. adviser by the end of the spring term of the first academic year. Advisers may be any Caltech faculty member working in an area related to bioengineering.

First Year Conversation. Before the end of the spring term of the first year in residence, each student meets with a faculty committee for a discussion of first-year progress and second-year plans. The committee must be composed of three faculty, plus the Ph.D. adviser(s), including a minimum of two Bioengineering faculty. The student will give a brief presentation on research progress and future plans, as well as discuss fundamentals related to the research area.

Admission to Candidacy. By the end of the spring term of the second year in residence, each student must complete the coursework requirement, prepare a candidacy report, and pass an oral candidacy exam. The report should be brief, describing research progress to date and outlining plans for the remaining doctoral research. The candidacy report should be submitted to the committee members one week before the oral exam. The committee must be composed of three faculty, plus the adviser(s), including a minimum of two Bioengineering faculty. The oral candidacy exam will include presentation of research progress, presentation of a proposed outline for the thesis, and questioning on fundamentals related to the research area. Students that complete the coursework requirement, prepare a candidacy report, and pass the oral candidacy exam will be recommended for candidacy. Students that are not admitted to candidacy by the end of the second year in residence will not be permitted to register in subsequent terms except with special permission from the option representative.

Thesis Examination. A final oral examination will be given after the thesis has been formally completed. The exam will consist of a public research presentation followed by a private defense with an exam committee. The committee must be composed of three faculty, plus the adviser(s), including a minimum of two Bioengineering faculty. The thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

Subject Minor
A student may, with the approval of the Bioengineering graduate option representative, elect a subject minor in Bioengineering. Such a program shall consist of 45 units of upper division course work in Bioengineering, with each course passed with a grade of C or better. Courses used to satisfy course requirements in the student's major option may not be used to satisfy the minor requirements. Approval of each program must be obtained from the Bioengineering graduate option representative.

Biology

Aims and Scope of the Graduate Program
Graduate students in biology come with very diverse undergraduate preparation—majors in physics, chemistry, mathematics, or psychology, as well as in biology and its various branches. The aims of the graduate program are to provide, for each student, individual depth of experience and competence in a particular chosen major specialty; perception of the nature and logic of biology as a whole; sufficient strength in basic science to allow continued self-education after formal training has been completed and thus to keep in the forefront of changing fields; and the motivation to serve his or her field productively through a long career.

In accordance with these aims, the graduate study program in biology includes the following parts: (a) the major program, which is to provide the student with early and intense original research experience in a self-selected subject of biology, supplemented with advanced course work and independent study in this subject; and (b) a program of course work designed to provide well-rounded and integrated training in biology and the appropriate basic sciences, which is adjusted to special interests and needs. An individual program will be recommended to each student in a meeting with the student's advisory committee (see below). The Division of Biology does not encourage applications from students who have pursued undergraduate study in biology at the Institute, because the broader perspective to be gained from graduate study in a different setting is considered to be essential for the full development of each student's potential. Exceptions to this policy may be considered by the faculty of the division if there are circumstances that indicate that it would be in the best interests of a student to pursue graduate study at the Institute.

Admission. Applicants are expected to meet the following minimal requirements: mathematics through calculus, general physics, organic chemistry, physical chemistry (or the equivalent), and elementary biology. Students with deficient preparation in one or more of these categories may be admitted but required to remedy their deficiencies in the first years of graduate training, with no graduate credit being granted for such remedial study. This will usually involve taking courses in the categories in which the student has deficiencies. In certain instances, however, deficiencies may be corrected by examinations following independent or supervised study apart from formal courses. Furthermore, the program in biology is diverse, and in particular fields such as psychobiology and experimental psychology, or in interdisciplinary programs, other kinds of undergraduate preparation may be substituted for the general requirements listed above.

When feasible, visits to the campus for personal interviews will be arranged before a final decision for admission is made. Graduate Record Examinations (verbal, quantitative, and an advanced test in *any* science) are required of applicants for graduate admission intending to major in biology. Applicants are encouraged to take these examinations and request that the scores be transmitted to Caltech, in November or earlier, to ensure unhurried consideration of their applications.

Master's Degree

The Division of Biology and Biological Engineering does not admit students for work toward the M.S. degree. In special circumstances the M.S. degree may be awarded, provided Institute requirements are met. In general the degree is not conferred until the end of the second year of residence. The degree does not designate any of the disciplines of the division, but is an M.S. in biology. The 135 units required by the Institute must include any two courses of a three-term series Bi 250 abc and Bi 252.

Degree of Doctor of Philosophy

Major Subjects of Specialization. A student may pursue major work leading to the doctoral degree in any of the following subjects: biophysics, cellular biology, developmental biology, genetics, immunology, microbiology, molecular biology and biochemistry, and systems biology. At graduation, a student may choose whether the degree is to be awarded in biology or in the selected major subject. Students who choose to work in Neurobiology may also qualify for a Ph.D. in Biology but are encouraged to enroll in the Neurobiology option.

Initial Advisory Committee. At the start of the first year of study, incoming students meet with the option representative or faculty member(s) specified by the option representative. The purpose of this meeting is to assist the student in organizing laboratory rotations, and to discuss what additional course work is desirable in light of the student's past record.

Rotations. The major initial responsibility of each student is to explore the various research possibilities available at Caltech before settling into a laboratory for their thesis research. Students are free to rotate in any laboratory at Caltech, not just those in the Division of Biology and Biological Engineering. First-year students should carry out a minimum of two laboratory rotations; three rotations are recommended. It is generally expected that rotations will last a full academic quarter; however, exceptions can be granted with the advance permission of the professor. Choice of laboratory should be made by the end of June of the first year except in extraordinary circumstances. Any exception should be discussed with the option representative.

Formal Classes. During the first year of graduate studies, students are required to take a course on responsible conduct of research (Bi 252), as well as any two courses of a three-term series (Bi 250 abc) that covers the breadth of fields represented in biology at Caltech.

During each year that they are matriculated in the Ph.D. program, students are required to take Bi 251 abc (Biolunch). Students will be required to present their thesis research in Biolunch during their second and fourth years of study.

In addition to these fixed requirements, during their time at Caltech all students must take one additional 200-series or upper-division 100-series course offered by the Division of Biology and Biological Engineering. Students may fulfill this requirement by taking three terms of Bi 250 abc.

Teaching. All students are to serve as teaching assistants for one quarter per year they are in residence, up through the third year.

Admission to Candidacy. The qualifying exam process that a student must complete to be admitted to candidacy is divided into two parts—an oral defense of the proposed thesis research and a written test of competency in the student's chosen area of research.

The Oral Exam. During winter quarter of the second year, a student is to set up a thesis proposal examining committee and prepare a proposal focused on the research project that they expect to pursue for their thesis research. The proposal is defended by the student in an oral presentation in front of the thesis proposal examining committee by the end of June. (Although it is anticipated that this exam will be completed by June of the second year, it can be delayed until August of the third year if the option representative agrees.) The examining committee comprises four faculty members, at least three of whom should hold full or joint professorial appointments in the Division of Biology and Biological Engineering. One of the members of the committee is appointed as chair. The chair of the thesis examining committee must be a Caltech faculty member other than the student's adviser. The adviser can, but need not be, a member of the examining committee. The members of the thesis proposal examining committee must certify passage of this exam. In the event that there is inadequate evidence of the capacity to do research, the student may be allowed to petition to re-take the oral exam at a later time. However, in cases where the committee deems it unlikely that the student will be able to pass a subsequent attempt, the student may be advised to leave the program. In any event, a student cannot remain in the program beyond August of the third year without having successfully completed the requirements for admission to candidacy, except in extraordinary circumstances and with the approval of the option representative and the dean of graduate studies.

The Written Exam. The written qualifying examination is taken in June of the student's second year in the division. Each student chooses one of the following subjects as a major: cellular and molecular neurobiology; developmental biology; genetics; immunology; molecular biology, biochemistry, and cell biology; or systems neurobiology. The exam chair for that major designs a program of study that culminates in the written exam. M.D./Ph.D. students are not required to take the written test of competency unless their adviser specifies that this is required.

Once a student has successfully completed the oral exam and written exam, he or she can apply to be admitted to candidacy. According to Institute regulations, this application process must be completed by the end of the third year of graduate study.

Thesis Advisory Committee Meetings. Once a student has been formally admitted to candidacy, he or she is to pick a thesis advisory committee (TAC). This committee is often the same as the thesis proposal exam committee, but that need not be the case. The thesis adviser must be a member of the TAC. The TAC typically has five members. At least three must be professorial faculty who hold a full or joint appointment in the Division of Biology and Biological Engineering, and at least four must be Institute professorial faculty. It is expected that students who have been admitted to candidacy will meet with the TAC once a year for the remainder of their time at Caltech. Students who fail to meet with their TAC in any one year may be deemed to not be maintaining satisfactory progress toward the Ph.D. degree and will be prevented from registering for the subsequent academic year.

Maintaining Satisfactory Progress. It is the policy of the biology option that a graduate student who is making satisfactory progress toward a Ph.D. degree can expect to continue as a registered student with full financial support. To be deemed as making satisfactory progress, a student is expected to fulfill the expectations listed below. In the event that satisfactory progress is not being made, a student can petition to receive the M.S. degree, for which they must have successfully completed one full year of graduate study.

Requirements for satisfactory progress include:

- Completion of the first-year course requirements during the first year.
- Joining a laboratory in which a student will perform thesis research before the end of the first year in residence.
- Passing the oral and written parts of the qualifying examina tion and completing admission to candidacy before the start of the year.
- Holding a thesis advisory committee meeting in each subsequent year of studies, and having the thesis committee verify that satisfactory progress is being made.
- Serving as a teaching assistant for one quarter of each academic year spent in residence through third year.
- Completing Ph.D. studies by the end of the sixth year.

In the event that the student, option representative, and adviser are in agreement, it is possible to make exceptions to the above guidelines and remain in good standing. Extension of thesis work beyond the end of the sixth year requires that the student petition the dean of graduate studies for permission to register for the seventh year. Extensions beyond the seventh year will be allowed only in unusual circumstances. Once a student has passed admission to candidacy, the responsibility for assessing satisfactory progress lies largely with the student's thesis advisory committee. If a majority of the committee deems that a student is not making satisfactory progress, the student is at risk of being removed from the program at any time at the discretion of the option representative.

Examination Committee. Requirements for the Ph.D. thesis and examination are determined by the Ph.D. examination committee that is appointed by the dean of graduate studies for each degree candidate. This committee is usually the same as the thesis advisory committee, but this need not be the case. The composition of the committee must be approved by the option representative. The committee usually has five members. At least three must be professorial faculty who hold a full or joint appointment in the Division of Biology and Biological Engineering, and at least four must be Institute professorial faculty.

Thesis and Final Examination. The thesis and associated publications are expected to demonstrate that the student has learned how to conceive, plan, and execute experimental and/or theoretical work that reveals new biological information. In addition, it must reveal a deep, broad, and rigorous understanding of the area of research to which the thesis is relevant.

Two weeks after copies of the thesis are provided to the examining committee, chairman, and option representative, the candidate collects the copies and comments for correction. At this time, the date for the final examination is set at the discretion of the major professor and the division chair. The final oral examination covers principally the work of the thesis, and according to Institute regulations must be held at least two weeks before the degree is conferred. Two copies of the thesis are required of the graduate for the Institute library.

Caltech-UCLA Medical Scientist Training Program (MSTP)
A joint program between Caltech and the UCLA Medical School has been established for the granting of the M.D./Ph.D. degree. Students do their preclinical and clinical work at UCLA, and their Ph.D. work with any member of the Caltech faculty, including the biology, chemistry, and engineering and applied science divisions.

Admission to this joint program is made through the usual UCLA MSTP process, checking a box indicating interest in the Caltech option. Students will be accepted into the joint program, funds permitting. The M.D. degree would be from UCLA and the Ph.D. would be awarded by Caltech. Ph.D. studies involving collaborations between laboratories at both institutions could lead to a joint degree with both schools being cited.

The current directors of the UCLA MSTP are Dr. Carlos Portera-Cailliau and Dr. Siavash Kurdistani, and Caltech professor Sarkis Mazmanian is the associate director. For more information, see http://mstp.healthsciences.ucla.edu.

Caltech-USC M.D./Ph.D. Program
A joint program between Caltech and the USC (Keck) Medical School has been established for the granting of the M.D./Ph.D. degree. Students do their preclinical and clinical work at USC, and their Ph.D. work with any member of the Caltech faculty.

Admission to this joint program is made through the usual USC process, checking a box indicating interest in the Caltech option.

Students will be accepted into the joint program, funds permitting. The M.D. degree would be from USC and the Ph.D. would be awarded by Caltech.

The current director of the USC M.D./Ph.D. program is Dr. Steven Mittleman, and Caltech professor Sarkis Mazmanian is the associate director. For more information, see http://keck.usc.edu/Education/Degrees_and_Programs/Professional_Degrees/MD/MD_Program/MD_PHD_Program.aspx.

Subject Minor
A student majoring in any non-biology option of the Institute may, with the approval of the Division of Biology and Biological Engineering, elect a subject minor in any of the subjects listed above under major subjects of specialization. Requirements for such a minor are determined by the faculty committee designated for each subject. A minor program in biology is also available to students of other divisions. Such a program shall consist of 45 units of upper division course work in the Division of Biology and Biological Engineering,

with each course passed with a grade of C or better. Approval of each program must be obtained from the biology graduate option representative. A student majoring in another division who elects a subject minor in biology may, if desired, arrange to have the minor designated as biology, rather than with the name of the specific minor subject.

Chemical Engineering

Aims and Scope of the Graduate Program

The general objective of the graduate work in chemical engineering is to produce individuals who are exceptionally well trained to apply mathematics, the physical, chemical, and biological sciences, and engineering to the understanding of systems involving chemical reactions and transport phenomena and to the development of new processes and materials. The program also strives to develop in each student self-reliance, creativity, professional ethics, and an appreciation of the societal impact of chemical engineering and the importance of continuing intellectual growth.

Admission. It is expected that each applicant for graduate study in chemical engineering will have studied mathematics, physics, chemistry, biology, and chemical engineering to the extent that these subjects are covered in the required undergraduate courses at Caltech. In case the applicant's training is not equivalent, admission may be granted but the option may prescribe additional work in these subjects before recommending him or her as a candidate for a degree.

Master's Degree

Course Requirements. At least 135 units of course work must be completed in order to satisfy the Institute requirements. These units must include ChE 151 ab, ChE 152, ChE/Ch 165, 18 additional units of advanced courses in chemical engineering, 27 units of science or engineering electives, and 18 units of general electives. The plan of study must be approved by the ChE option representative in the Graduate Degree Progress in Regis. Finally, the M.S. requirements include at least 27 units of research, ChE 280, which represents two terms of research under the supervision of a chemical engineering faculty member or a two-term industrial research or development project performed with a member of the faculty in cooperation with professional staff at a local industrial laboratory. At least three weeks before the end of the final term of residence, a research report on the work performed under ChE 280 must be submitted to a designated member of the faculty, who will ask that it be read and approved by two members of the faculty. In addition, the fulfillment of the research report requirement must be approved by the student's advisor in the Graduate Degree Progress in Regis. Doctoral students who have been admitted to candidacy can use their approved candidacy report to satisfy the research report requirement of the M.S. degree.

Degree of Doctor of Philosophy
The work leading to the Ph.D. degree prepares students for careers in universities and in the research laboratories of industry and government. Usually the first year of graduate work is principally devoted to course work in chemical engineering and related subjects. Time is also devoted during this period to the choice and initiation of a research project. During the second year, the student is expected to spend at least half-time on research, and to complete the course work and candidacy requirements.

Admission. Upon arrival at Caltech, each prospective Ph.D. student will meet in consultation with members of the faculty so that they may evaluate the level of the student's preparation with respect to that expected at the Ph.D. level in the areas of kinetics, thermodynamics, and transport phenomena. These consultations are held to help the student set up a course program for the first year of study. A written copy of the recommendations will be entered into each student's permanent file.

Research Adviser. During the first term, the faculty meets with the first-year grad students to propose topics for Ph.D. research. Following these meetings, the students are expected to meet individually with the various faculty members to discuss proposed research and generally obtain information for choosing a research adviser. At the end of the first term, each student is required to submit three faculty names, listed in order of preference. Every possible effort will be made to accommodate the student's first choice, subject to an opening in the desired research group, availability of necessary funding, etc. The final decision will be made by the chemical engineering faculty in consultation with the students.

Oral Qualifying Exam. Each student is required to take a subject qualifying examination at the end of the second quarter in residence, the purpose of which is to examine expertise in kinetics, thermodynamics, and transport phenomena. The intended level of the exam is approximately that of the corresponding undergraduate courses at Caltech. The format and topics of the examination are distributed to the first-year students at the beginning of the fall quarter. The results of the exam in combination with performance in the graduate courses will determine a student's continuing in the graduate program.

Course Requirements. Students are required to take ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and an additional course from a designated list, selected in consultation with his/her adviser. Each student is required to complete either a subject minor, or a general program of courses outside chemical engineering consisting of at least 54 units. The choice of the 54 units is subject to certain guidelines and restrictions included in the chemical engineering graduate studies guide. The general program of courses must be approved in advance by the option representative. It is intended that the courses chosen should constitute some integrated program of study rather than a randomly chosen collection of courses outside chemical engineering. Within these guidelines, the only course specifically excluded is research in another option. A grade of C or better is required in any course, and a grade-point average of at least 3.0 is expected. The requirements for a subject minor in any option are listed in this catalog.

Candidacy Report/Examination. Before the end of the spring quarter of the second year of residence, each student must submit a written progress report on his or her research for approval by a specially constituted candidacy committee consisting of faculty members familiar with his or her general area of research. An oral examination is subsequently held by this committee to evaluate the student's ability to carry out research at the Ph.D. level. A student who fails to satisfy the candidacy requirements by the end of the second year in graduate residence will not be allowed to register in a subsequent term except by special permission of the option and the dean of graduate studies.

Admission to Candidacy. To be admitted to candidacy, the student must have passed the qualifying and candidacy examinations, must have had the candidacy report approved, and must have submitted an approved list of courses already taken or to be taken.

Thesis Review Committee. After the student passes the second-year candidacy exam, the candidacy committee becomes the "de-facto" Thesis Review Committee, which will be responsible for reviewing the student's progress. The committee must be convened during the 4th year of residency, and every year thereafter to review progress, suggest improvements in research, or resolve any issues that could potentially delay graduation beyond the 5th year of residency. It is the responsibility of the student to organize the annual meetings of the Thesis Review Committee, which may be convened at any time during the year but <u>at least three months</u> before registration for the next academic year. Sequential registration beyond the 4th year is subject to written approval by the Thesis Review Committee and the ChE Option Representative. In order to expedite the review, the student should submit a two or three page *concise outline* of progress and of proposed future research to each member of his/her committee before the annual review meeting.

Final Examination and Thesis. See pages 306-309 and the option graduate studies guide for regulations concerning final examinations and theses. A copy of the corrected thesis is to be submitted to the chemical engineering graduate secretary for the chemical engineering library.

The final examination will include the candidate's oral presentation and defense of his or her Ph.D. thesis.

All Ph.D. students are required to perform a minimum of 24 term-hours of chemical engineering graduate teaching assistantship (GTA) duties during their studies. GTA duties will normally be assigned after the first year in residence. Serving as TA for classes outside chemical engineering may be allowed at the discretion of the option representative.

Subject Minor

Graduate students electing a subject minor in chemical engineering must complete 54 units of graduate courses in chemical engineering that are approved by the chemical engineering faculty. The 54 units will consist of no more than 24 units from ChE 101, 103 abc, 105, 118, and 120, and at least 36 units from ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and a list of chemical engineering courses provided by the option representative. A 3.0 GPA is required for the courses taken.

Graduate Studies Adviser, Option Representative, and Chemical Engineering Graduate Studies Committee. During graduate studies, students will interact with several members of the chemical engineering faculty. The most intensive interaction will be with the research adviser, who will advise on all aspects of Ph.D. research and course work and will approve various formal requirements. The student will also interact with the members of the thesis review committee on matters relating to research progress, and the ChE option representative on any other matters concerning graduate studies. During the first year, the ChE option representative will advise the students about choice of research adviser, choice of courses, and Ph.D. qualifying exams. The option representative is responsible for GRA (graduate research assistantship) or GTA (graduate teaching assistantship) assignments, beyond the first year, and for approval of the Candidacy and Thesis Review Committees and other formal requirements for the M.S. and Ph.D. degrees. Students may contact either of these two faculty members regarding any questions or problems. In a case where the relationship between a student and his or her research adviser becomes strained and the student desires advice or help from other faculty, he or she should consult with the Chemical Engineering Graduate Studies Committee, consisting of the option representative, the graduate studies adviser, and the option executive officer.

Additional Information

Additional information about graduate study requirements and procedures is provided in the chemical engineering graduate studies guide, distributed annually to first-year chemical engineering graduate students.

Chemistry

Aims and Scope of the Graduate Program

The Caltech Chemistry option offers a program of graduate study leading to the Ph.D. degree, with the goal of preparing students for a lifetime of independent research and scientific leadership in the chemical sciences, through careers in academia, industry or government. Modern chemistry strives to achieve a molecular-level understanding of the natural world and thus forms the basis for much of modern science, including biology, medicine, materials, nanotechnology, energy and environment. The program of study, while anchored in the traditional areas of organic chemistry, inorganic chemistry, chemical biology, biochemistry and biophysics, chemical physics and theoretical chemistry, is flexible and highly interdisciplinary.

The graduate program in chemistry emphasizes research. This emphasis reflects the Institute's traditional leadership in chemical research and the conviction that has permeated the Division of Chemistry and Chemical Engineering from its founding, that participation in original research is the best way to awaken, develop, and give direction to creativity.

The program is designed to encourage students to begin their research early in their first year. Students can elect to do research that crosses the boundaries of traditionally separate areas of chemistry, for in this relatively compact division, they are encouraged to go where their scientific curiosity drives them. A thesis that involves more than one adviser is not uncommon, and interdisciplinary programs with biology, physics, geology, chemical engineering, and environmental science and engineering science are open and encouraged.

An extensive program of seminars will enable students to hear of and discuss notable work in chemical physics, organic chemistry, inorganic chemistry and electrochemistry, organometallic chemistry, and biochemistry and molecular biophysics. Graduate students are also encouraged to attend seminars in other divisions.

Learning Outcomes
Students upon whom are conferred the Ph.D. degree have provided evidence of independent scholarship and scientific creativity through the performance of original research, which is described in their doctoral thesis and defended orally. Students must also demonstrate an ability to conceive new research directions by preparing and defending a set of written research propositions.

Course Program
A student is required to complete at least five courses, each being nine units or more, in science or engineering. At least one course must be in a field substantially outside the research area of the student. Courses may be either inside or outside the chemistry option, must be numbered 100 or greater, and must be taken on a letter-grade basis with a grade of B or above. The student should discuss, with his or her advisor, which courses best serve his or her individual needs. The program of courses must be approved by the research advisor and by the Chemistry Graduate Study Committee.

Master's Degree
Students are not ordinarily admitted to graduate work leading to an M.S. degree. Under special circumstances, and with prior approval of the Graduate Study Committee, a master's degree can be obtained. All master's programs for the degree in chemistry must include at least 45 units of chemical research and must satisfy the Course Program described above. The remaining electives may be satisfied by advanced work in any area of mathematics, science or engineering, or by chemical research. Two copies of a satisfactory thesis describing this research, including a one-page digest or summary of the main

results obtained, must be submitted to the divisional graduate secretary at least 10 days before the degree is to be conferred. In addition, the fulfillment of the thesis requirement must be signed off by a designated faculty member on the M.S. candidacy form and a final copy of the thesis submitted to the Graduate Office no later than two weeks before the degree is to be conferred. The copies of the thesis should be prepared according to the directions formulated by the dean of graduate studies and should be accompanied by a statement of approval of the thesis, signed by the advisor directing the research and by the chair of the Chemistry Graduate Study Committee.

B.S./M.S. Joint Degree

Under special circumstances, exceptional undergraduate students may be awarded a joint B.S./M.S. degree in Chemistry. Students with demonstrated academic excellence may petition the Chemistry Graduate Studies Committee and the Chemistry Curriculum and Undergraduate Studies Committee. Petitions should be submitted no later than Add Day of the Spring of their second year, but students are strongly encouraged to contact the Graduate Option Representative as early as possible, who will assign them to an academic graduate advisor. They must fulfill all institute and option requirements for both the B.S. and M.S. degrees; no courses can satisfy B.S. and M.S. degree requirements simultaneously. Coursework for the M.S. portion of the degree must be taken from courses numbered 100 and above on a letter-grade basis, and passed with a grade point average of 3.5 or better. As a junior, students must take 27 units of research in Ch82 and complete all requirements including a written thesis and oral presentation. The thesis must be judged exceptional by a committee comprising the research advisor, graduate academic advisor, Ch82 instructor, and Chair of the Graduate Studies Committee, in order to continue with the B.S./M.S. program. As a senior, the students must take 27 units of research as Ch182 and is expected to satisfy all requirements, including submission of a Master's Thesis and oral presentation. No additional units of research beyond these 54 units can be used to meet the course requirements.

Degree of Doctor of Philosophy

Selecting a Research Project. Soon after a new graduate student arrives in the laboratories, he or she attends a series of orientation seminars that introduce students to the active research interests of the faculty. Students then meet with each of five or more faculty whose fields attract them, to discuss in detail potential research problems. They eventually settle upon the outlines of a research problem that interests them and select a specific research advisor (or set of co-advisors). Neither students nor faculty can make a commitment to an advisor-advisee relationship prior to the end of the first month of the fall term. Students typically begin research during their first academic year.

Candidacy. To be recommended for candidacy for the doctor's degree in chemistry, in addition to demonstrating an understanding and knowledge of the fundamentals of chemistry, a student must give satisfactory evidence of proficiency at a high level in the primary field of interest, as approved by the division. This is accomplished by an oral candidacy examination, which must be held during or before the fifth term of graduate residence (excluding summer terms). The candidacy committee shall consist of the thesis advisor(s) and two additional faculty members; at least two of the three members must be chemistry faculty. The committee should be considered as a resource for the student for the remainder of his or her studies. At the candidacy examination, a student is asked to demonstrate scientific and professional competence and promise by discussing a research report and propositions as described below.

The research report should describe progress and accomplishments to date and plans for future research. Two original research propositions, or brief scientific theses, must accompany the report, and at least one must be well removed from the student's field of research. These propositions should reflect his or her breadth of familiarity with the literature, originality, and ability to pose and analyze suitable scientific research problems. The research report and propositions must be in the hands of the examining committee one week before the examination.

The result of the candidacy examination may be either (a) pass, (b) fail, or (c) conditional. Conditional status is granted when the committee decides that deficiencies in a student's research report, propositions, or overall progress can be remedied in a specific and relatively brief period of time. In order to change conditional to pass status, the student must correct the indicated deficiencies or in some cases schedule a new examination the following term. He or she must be admitted to candidacy at least three terms before the final oral examination. A student cannot continue graduate work in chemistry (nor can financial assistance be continued) past the end of the sixth term of residence without being admitted to candidacy, except by petitioning the division for special permission. This permission, to be requested by a petition submitted to the Graduate Study Committee stating a proposed timetable for correction of deficiencies, must be submitted before registration for each subsequent term (including the summer following the sixth term of residence) until admission to candidacy is achieved.

Language Requirement. There is no formal foreign language requirement for the Ph.D. in chemistry. However, the division believes strongly in the professional importance to chemists of knowledge of foreign languages and encourages their study prior to graduate work or while in graduate school.

Ph.D. Thesis Committee. In the third year, the student in consultation with their advisor will form their Ph.D. thesis committee. This committee will comprise at least four faculty members and will generally consist of the original candidacy committee plus an additional member of the faculty; at least three of the members must be from the chemistry option. The student must meet with their committee annually, beginning in the third year. At these informal meetings, the student will update the committee on the status of their research.

Fourth Year Progess Meeting. Before the thirteenth academic term of graduate residence (excluding summer terms), the student will be expected to demonstrate satisfactory progress in the course of thesis research. To this end, an informal meeting with the Ph.D. thesis committee will be held, at which time the student will present an oral summary of research completed to date as well as an outline of future research plans. Following the presentation, an appropriate timetable for completion of the degree requirements will be discussed and agreed upon. If the student has not progressed sufficiently, completion of the Ph.D. may be considered inappropriate.

Length of Graduate Residence. Any graduate student who anticipates a need to register for a twenty-fourth academic term must hold a meeting of his or her thesis committee and present the institute-required petition for permission to register that includes a plan of action for the period of the requested registration and a specific date for the completion of the degree requirements. This petition must be approved by the Thesis Committee, by the chair of the Chemistry Graduate Study Committee and, in cases where financial support is an issue, by the executive officer or division chair, before it is forwarded to the Dean of Graduate Studies. Financial support of graduate students who are required to petition to register will not normally be provided through teaching assistantships. Failure to complete the degree requirements by the date specified in the petition would require the entire approval process to be repeated. This process must be repeated for every subsequent year.

Thesis and Final Examination. The final examination will consist in part of the oral presentation and defense of a brief résumé of the student's research and in part of the defense of a set of propositions he or she prepares. Three original research propositions are required. No more than one of these may be a carryover from the candidacy examination, and at least one must be well removed from the field of research. Each proposition shall be stated explicitly and the argument presented in writing with adequate documentation. The propositions should display originality, breadth of interest, and soundness of training; a student will be judged on the selection and formulation of the propositions as well as on the defense of them. Formulating a set of propositions should begin early in the course of graduate study.

To emphasize the importance of these propositions, there will be a separate examination on the three propositions by the Ph.D. thesis committee. This examination on the propositions is normally taken after the thesis research progress meeting, but not less than 10 weeks in advance of the final doctoral examination. A copy of the propositions, along with suitable abstracts, must be submitted to the examining committee and to the division graduate secretary not less than two weeks before the propositions examination.

These propositions must be acceptable to the committee before the final doctoral examination can be scheduled.

A copy of the thesis must be submitted to each member of the thesis committee not less than two weeks before the final doctoral examination. A copy of the thesis should also be submitted to the Graduate Office for proofreading three weeks prior to the final doctoral examination. One reproduced copy of the thesis, corrected after proofreading, is to be submitted to the division graduate secretary for the divisional library. Two final copies (one on Permalife paper) are to be submitted to the Graduate Office.

Subject Minor
Graduate students in other options taking chemistry as a subject minor will be assigned a faculty adviser in chemistry by the Chemistry Graduate Study Committee. In consultation with this adviser, the student will work out an integrated program of courses, including at least 45 units of formal course work at the 100 level or above. This program must be approved by the Chemistry Graduate Study Committee, and a grade point average of 3.0 in the approved program will be required.

Civil Engineering

Aim and Scope of the Graduate Program
Civil Engineering (CE) research and study are offered through the Department of Mechanical and Civil Engineering (MCE). The degrees of Doctor of Philosophy (Ph.D.) and Master of Science (M.S.) are offered. The M.S. degree is normally only awarded to students who expect to pursue the Ph.D. degree in civil engineering and who do not already have an M.S. degree in civil engineering. In general, students who intend to work full-time toward the Ph.D. degree as a final degree objective are admitted to the civil engineering graduate program.

The aim of the graduate program in civil engineering at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, with a strong background in the basic and engineering sciences. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Preparation for the Graduate Program
Students who have not specialized in civil engineering as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may provide a suitable background as well. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty.

Master's Degree Description and Requirements

The degree of Master of Science in civil engineering is only awarded to students who do not already have an M.S. degree in civil engineering. The degree will be awarded upon request by students who have fulfilled the requirements. Only in exceptional cases is there admission to the M.S. program as the final degree objective.

A minimum of 138 units of courses numbered 100 or above, that meet the required master's program listed below, must be passed with a grade of at least C for completion of the master's degree in civil engineering. All units must be taken for grades, except for courses offered only on a pass/fail basis. The M.S. degree in civil engineering is typically completed within the first two years of residency at Caltech.

Each student's program must be approved by the adviser and option representative in mechanical and civil engineering before registering for the course.

Required Master's Program

a) Graduate civil engineering core (45 units). These units should provide a solid base for the student's engineering interest. The courses should be selected from the core subjects list Areas 1-3 of the civil engineering Degree of Doctor of Philosophy Description and Requirements section.
b) Mathematics, engineering, and research electives (63 units). Students who have not taken the equivalent of ACM 100 ab are required to take ACM 100 ab for 24 units. Research up to a maximum of 27 units.
c) Free electives (27 units). These units may be selected from any course with a number of 100 or greater, except that research units may not be included.
d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

Degree of Doctor of Philosophy Description and Requirements

The Ph.D. degree in civil engineering is focused on research. Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project resulting in an original contribution to the field which is documented by a thesis is required. Institute requirements for the Ph.D. degree are described in the section on degree requirements. A minimum of three academic years in residence as a graduate student are required by the Institute, and two or more additional years are usually needed for preparation of the thesis.

Advising and Thesis Supervision. An interim adviser is appointed for each student upon admission to a graduate degree in civil engineering. The interim adviser will serve as the primary mentor until the student finds a research adviser. It is the responsibility of the student to find an academic and research adviser within three terms of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee within four terms of graduate residence at Caltech. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering. The committee shall meet as requested by the student. Further, the committee shall meet annually to review progress and to approve the registration of the student beyond the fifth year of graduate residence at Caltech.

The adviser and the thesis advisory committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in civil engineering, the student must, in addition to meeting the general Institute requirements, do the following:

- Obtain the agreement of a professorial faculty member to serve as his or her academic and research adviser before the end of the third term of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee before the end of the fourth term. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering.
- Pass both subject and research components of the oral candidacy examination before the end of the eighth term of graduate academic residence at Caltech. If the student has chosen a subject minor, an examination on the subject of that program may be included at the request of the discipline offering the subject minor.
- Complete a minimum of 195 units of courses numbered 101 or above, that meet the required Ph.D. program listed below. All units must be taken for grades and passed with a grade of at least a C, except for courses offered only on a pass/fail basis. The course work towards the Ph.D. degree in civil engineering is typically completed within the first three years of residency at Caltech.

Required Ph.D. Program

a) Civil engineering core subjects (45 units). Course work in a minimum of two core civil engineering subjects, minimum of 18 units each of two subjects, spanning at least two broad areas listed below. Most students prepare for the subject candidacy exam by taking the recommended set of courses listed below in Areas 1-3, plus math. These units may also be used in the student's program for the master's degree Examples of suitable courses are given in parentheses.

Core CE Subjects
Area 1
Fluid Mechanics (Ae/APh/CE/ME 101 abc)
Mechanics of Structures and Solids (Ae/AM/CE/ME 102 abc)

Area 2
Dynamics & Vibrations (AM/CE 151 ab)

Area 3
Structural & Earthquake Engineering (CE 160 ab)
Seismology (CE 181 ab, Ge 162)

The student may petition the mechanical and civil engineering option representative to accept alternate subjects or areas. These changes should retain core civil engineering knowledge, should not be a sub-specialty of one of the listed areas, and should represent sufficient breadth. The approval is not automatic; such petitions are submitted rarely and many have been denied in the past. The petition must be submitted to the option representative and approved before the student registers for the course.

b) Additional engineering or science courses, with a course number 101 or above (63 units). Pass with a grade of at least C, courses that pertain to the student's specialty and are approved by the thesis advisory committee.
c) Advanced mathematics or applied mathematics (27 units). Pass with a grade of at least C, chosen in consultation with the adviser from the following list: ACM 101 or higher, CDS 140, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.
d) Graduate engineering seminar (6 units). Pass six terms of AM/CE/ME 150 abc, within twelve terms, 3 years, in residence at Caltech.
e) Research (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

The requirement of a minimum grade of C will be waived for an advanced course which is offered only pass/fail. The faculty will evaluate the student's research progress, class performance, adviser's input, and oral candidacy exam results to determine whether a student will be admitted to or be able to maintain candidacy for the Ph.D. degree.

Registration Beyond the Sixth Year of Graduate Residence. The annual approval of the Ph.D. dissertation supervision committee is necessary for registration beyond the twenty-fourth academic term of graduate residence at Caltech.

Thesis and Final Examination. The thesis examination will be given after the thesis has been formally completed. This examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. The format of the examination can be chosen from the following two options, by the student, in consultation with their research advisor: (i) a public seminar presented by the candidate, with an open question period, followed by a private examination by the examining committee or (ii) a private presentation to the examining committee followed by the examination, with a public seminar on another date. The examining committee shall consist of a minimum of four voting members, three of whom must be Caltech faculty; two members must be from MCE. The thesis defense committee shall be chaired by a committee member who is an MCE Caltech professorial faculty member and not the student's adviser.

Subject Minor
A student majoring in another branch of engineering or another division of the Institute may, with the approval of the faculty in the department of mechanical and civil engineering and the faculty in his or her major field, elect civil engineering as a subject minor. The program of courses must differ markedly from the major subject of study or research, and must consist of at least 54 units of advanced courses (101 or above) approved by the faculty in mechanical and civil engineering.

Computation and Neural Systems

Aims and Scope of the Graduate Program
An integrated approach to graduate study combining computation and neural systems is organized jointly by the Division of Biology and Biological Engineering, the Division of Engineering and Applied Science, and the Division of the Humanities and Social Sciences. This curriculum is designed to promote a broad knowledge of aspects of molecular, cellular, and systems biology, cognitive neuroscience, computational biology and computational neuroscience, information and learning theory, emergent or collective systems, and computer science and electrical engineering in conjunction with an appropriate depth of knowledge in the particular field of the thesis research. For more details, see http://www.cns.caltech.edu.

Admission. Ideal applicants will have a Bachelor of Science degree or equivalent with a strong quantitative background and some facility with computer programming. They will have shown an interest in understanding the brain and/or in autonomous intelligent systems. All applicants are strongly encouraged to submit their Graduate Record Examination (GRE) verbal and quantitative scores.

Advisory Committee and TA Requirement. An advisory committee of three CNS faculty members is constituted for each student by the CNS admissions committee upon admission to the program. The faculty in whose lab the student is staying first chairs this committee. The advisory committee meets with the student when he or she arrives, guides and approves first-year course choices, and answers questions and offers advice about the program and the way of life in CNS. The CNS faculty are available to students during the year for formal and/or informal discussions.

It is expected that each graduate student will serve as a teaching assistant in one or two CNS courses during his or her residency at Caltech as part of the Ph.D. graduation requirement.

Master's Program

Only students who expect to pursue the Ph.D. degree will be admitted to the option. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the option breadth requirements (see following section), the completion of a master's thesis, and receiving from a candidacy examination oral committee a recommendation for awarding the degree.

Laboratory Rotations. Mandatory rotations through research groups (labs) provide a unique opportunity for the student to experience the CNS culture. To broaden the student's knowledge and to provide familiarity with different techniques and ways of thinking or doing research, each student should carry out three 12-week laboratory rotations (one per term) during the first year, and should engage in research. During each rotation, the student is expected to take part in the life and routine of the lab by attending lab meetings, participating in research projects and discussions with members of the lab, and meeting monthly with the faculty of that lab to discuss science.

Course Requirements. Six nine-unit courses are required during the first year: CNS/Bi/Ph/CS/NB 187, either Bi 9 or equivalent, or Bi/CNS/NB 150, a neurobiology or modeling course, a math course, and two other CNS, Bi, EE, ACM, or Ph courses (for example, a schedule of CNS/Bi/EE/CS/NB 186, CNS/Bi/Ph/CS/NB 187, Bi/CNS/NB 150, and CS/CNS/EE 156 satisfies this requirement). CNS students are required to take two additional classes: the one-unit survey course CNS 100, and the four-unit course Bi 252. These eight courses must be taken for letter grades. Students are free to take additional classes, and a research adviser may require that a student take a specific, complementary course as a requirement for joining his or her lab.

Candidacy. Four faculty, including the three faculty in whose labs rotations have been done, should be on the student's candidacy exam committee. At the end of the first year, the student is expected to decide on a research group and begin work there. The first summer is thus expected to be spent entirely on research in that lab. To be recommended for candidacy you are required to pass two tests: the general knowledge exam, and the research and candidacy exam. These exams are supervised by the CNS option representative.

The general knowledge exam satisfies the breadth requirement. A list of about 100 questions, grouped by category, is available at http://www.cns.caltech.edu, providing a clear idea of the scope of knowledge that each student is expected to know well. Students are encouraged to organize working and discussion groups to prepare for this exam; the format and implementation of such a system, however, is left to the students.

This is an oral exam with the four faculty (including the heads of the student's three rotation labs and one other chosen for "breadth," of whom one can be from outside Caltech). It should be scheduled by the student (who contacts the committee members) to take place during the last six weeks of the third term of year one. For the exam, the student must answer questions (from more than one category) taken from the list, which is modified each year. (The exam can be retaken after three months.)

The research and candidacy exam satisfies the depth requirement. During year two, the student is expected to produce a piece of work of a quality sufficient to be presented at a professional meeting. (The objective of this description is to offer a way to calibrate the level of expected research achievement and involvement. Professional acceptance of the abstract or paper is not a requirement for passing candidacy.) This work is presented in an oral exam in spring term of year two, before the same exam committee (if possible) that conducted part one of the exam. The exam focuses exclusively on research (accomplished and/or planned). During year two, the student may take other courses, as needed, but is expected to present a high standard (quality, originality) of research at the time of this second part of the candidacy exam.

Subject Minor

Students majoring in other fields may take a subject minor in CNS, provided the program is supervised by a CNS adviser, is approved by the CNS option representative, and consists of 45 units, including Bi/CNS/NB 150, CNS/Bi/Ph/CS/NB 187, Bi 252, and other CNS cross-listed classes. A subject minor is not required for the Ph.D. degree in CNS.

Computational Science and Engineering

Aims and Scope of the Minor

Computational science and engineering (CSE) may be pursued as a subject minor by graduate students who are pursuing Ph.D. degrees in any option. The CSE minor is intended to supplement one of Caltech's graduate degrees and is designed for students who wish to broaden their knowledge of CSE beyond their major field of study. The CSE minor is also intended to recognize graduate students' interest in and dedication to CSE as demonstrated by the successful completion of a program of study in the field. Completion of the CSE minor program of study will be recognized on the Ph.D. diploma by the statement, "…and by additional studies constituting a minor in Computational Science and Engineering."

Requirements. To receive the CSE minor, graduate students must fulfill the following requirements.

- 18 units (two terms) from the following list: ACM 106 ab, CMS/ACM 113, ACM 210 ab, ACM 216.
- 18 units (two terms) from the following list: CS/EE/Ma 129 abc, CS 138 abc, CS 139 abc, CS 150, CS/CNS/EE 156 a.

- 9 units (one term) from the list: Ae/AM/CE/ME 214 abc, Ae/AM/ME 232 ab, Ay 199, Ch 121 ab, GE 263, Ph/CS 219 abc.

All courses to be applied toward the CSE minor requirements must be taken on a graded basis, and students must obtain a grade of B or higher in all courses. Courses that are used to satisfy the CSE minor cannot be used to satisfy course requirements in the major options unless absolutely required by the option. Courses taken as part of the CSE minor are counted toward the total number of units required for the completion of the Ph.D. degree.

CSE Minor Administration

The CSE minor is administered by an oversight committee consisting of three faculty members reporting to the chair of the engineering and applied science division. In consultation with their advisers and, if needed, with the CSE Oversight Committee, students formulate a program of approved courses individually tailored to each student's background and needs, with the objective that the student achieve a level of competence in specific subjects relevant to CSE. Students must petition the CSE Oversight Committee for approval of their program of study. Upon completion of the program of study, the CSE Oversight Committee will verify that the CSE minor requirements have been fulfilled.

Computer Science

Aims and Scope of the Graduate Program

Graduate study in computer science within the Computing & Mathematical Sciences department is oriented principally toward Ph.D. research. The course work and thesis requirements for the M.S. degree are a required part of the Ph.D. program. There is no admission to the M.S. program as the degree objective. However, Caltech undergraduates wishing to continue an undergraduate research project after completing their B.S., leading to an M.S. degree, may apply in their junior or senior years for admission to the joint B.S./M.S. degree program (see page 304). Students interested in this option should have a faculty sponsor, and should consult with the option representative.

Students entering the graduate program with an M.S. degree from another school may transfer credit for course work as appropriate. A student may petition the option representative to have a prior M.S. thesis or equivalent accepted in lieu of a Caltech M.S. thesis; no Caltech M.S. will be granted in this case.

The Ph.D. program requires a minimum of three academic years of residence. The M.S. should be completed within the first two years.

Students must maintain high academic standards during their graduate residence. A student's Ph.D. research must exhibit originality in the formulation, analysis, and solution of a problem that is significant to the field of study. The option representative and executive officers are available to discuss concerns regarding academic progress.

Master's Degree

There are five requirements to fulfill for the M.S. in computer science:

- Total units. Completion of a minimum of 135 units of courses numbered 100 or greater, including M.S. thesis research (CS 180). The student will consult with the adviser to ensure balance in the course work.
- Advanced courses in computer science. Completion of a minimum of 54 units of CS courses numbered 100 or greater in addition to units earned for reading, research, projects, and the M.S. thesis.
- Units outside computer science. Completion of a minimum of 27 units outside computer science. Courses jointly listed with computer science cannot be used to fulfill this requirement.
- Breadth. Toward the end of the first year, all incoming students must successfully pass a diagnostics exam administered by the faculty. Its purpose is to ensure a solid and broad knowledge in computer science, and/or to direct the students to necessary courses and reading.
- M.S. thesis. At the end of the second year, students must have completed a minimum of 45 units of CS 180, had their M.S. thesis approved by a computer science faculty member, obtained the signature of a designated computer science faculty member on the M.S. candidacy form, and submitted a copy of the M.S. thesis to the Graduate Office no later than two weeks before the degree is to be conferred.

Degree of Doctor of Philosophy

Candidacy. To be recommended for candidacy, a student must have completed the M.S. program, have entered upon a course of research approved by his or her thesis adviser, and have passed a candidacy oral examination. The candidacy oral examination is administered by a committee that consists of four faculty, is approved by the option representative, and is chaired by the adviser. The examination ascertains the student's breadth and depth of preparation for research in the chosen area. The examination should be taken within the first three years of graduate study.

Advising and Thesis Supervision. In order to facilitate close supervision and a highly research-oriented environment, each student is admitted directly to an adviser and research group. A course of study is determined in consultation with the adviser. Occasionally students will be admitted into more than one group. Changes in affiliation may occur with the common consent of the student and the new adviser.

Students meet regularly with their adviser throughout their time at Caltech, and are encouraged to do the same with other members of the faculty.

Thesis and Final Examination. A final oral examination will be scheduled and given after the Ph.D. thesis has been submitted for review to the student's adviser and thesis committee; the latter consists of at least four faculty approved by the option representative, and is chaired by the adviser. The thesis examination is a defense of the thesis research and a test of the candidate's knowledge in his or her specialized fields.

Subject Minor in Computer Science
A subject minor is not required for the Ph.D. degree in computer science. However, students majoring in other fields may take a subject minor in computer science, provided the program is supervised by a computer science faculty adviser, is approved by the computer science option representative, and consists of 45 units sufficiently removed from the student's major program of study.

Computing and Mathematical Sciences

Aims and Scope of Graduate Program
Algorithmic thinking is emerging as a fundamental tool for all researchers, not just computer scientists. Algorithmic thinking now drives disciplines ranging from statistics and electrical engineering to biology and physics to economics and the social sciences. Computing and Mathematical Sciences (CMS) is an interdisciplinary PhD program that trains students to apply algorithmic thinking to problems across science and engineering. Our research mission is to build the mathematical and algorithmic foundations required to move from data to information to action. Students will study structures and mechanisms that store, process, and communicate information and that make decisions based on this information. These systems may be expressed in silicon and called computers, in lines of code called programs, or in abstract notation called mathematics. They may appear in economics as markets or social networks, as sequences of amino acids in DNA, or in the organic structure of the human brain.

Master's Degree
Only students who expect to pursue the Ph.D. degree will be admitted to the option. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the core course requirements, and receiving a recommendation for awarding of the degree from the preliminary exam committee.

Degree of Doctor of Philosophy
Institute requirements for the Ph.D. degree are described in the section on degree requirements. Approximately two years of coursework are required, and two or more years are usually needed for preparation of the dissertation.

Admission to Candidacy

To be recommended for candidacy for the Ph.D. degree in Computing and Mathematical Sciences the student must, in addition to meeting the general Institute requirements, do the following:

1. First-year core course requirement: The following courses are required to be completed during the first year: CMS/ACM 104, CMS/ACM 113, CMS/ACM 116, CMS/CS 139, CMS/CS/EE 144, CMS/CS/CNS 155.
2. Depth requirement: At least 27 units of courses must be completed within one particular subject area. The plan for these 27 units must be approved with the student's adviser.
3. Breadth requirement: At least 27 units of 100+ level courses must be completed in Engineering, Science, Mathematics, or Economics.
4. Preliminary Examination: All students must pass a preliminary examination, which is an oral exam that is administered by a committee consisting of at least three faculty selected by the option representative. The exam will occur during the student's first year.
5. Candidacy Examination: All students must pass a candidacy oral examination will be administered by a committee that consists of at least four faculty, is approved by the option representative, and is chaired by the student's research adviser. The examination will ascertain the student's breadth and depth of preparation for research in the chosen area. The examination will be taken within the first three years.

Advising and Thesis Supervision

Upon admission, each student will be assigned a primary adviser in the option. This adviser will be replaced by a research adviser (possibly the same faculty member) once a direction of specialization is determined, and not later than the beginning of the second year. Before candidacy, students are required to attend the CMS colloquium, CMS 290abc, each term. After completion of the candidacy exam, each student will form a thesis committee (possibly the same as the candidacy committee) consisting of at least four faculty approved by the option representative, and chaired by the adviser. The thesis committee will meet as needed, but at least yearly, in order to advise the student.

A final oral examination will be scheduled and given after the PhD thesis has been submitted for review to the student's adviser and thesis committee. The thesis examination is a defense of the thesis research and a test of the candidate's knowledge in his or her specialized fields. Normally, the defense will consist of a one-hour public lecture followed by an examination of the thesis by the thesis committee.

Control and Dynamical Systems

Aims and Scope of the Graduate Program

The option in control and dynamical systems (CDS) is open to students with an undergraduate degree in engineering, mathematics, or science. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty. In some cases the student may be required to make up undergraduate deficiencies in engineering science courses.

The CDS option, as part of the Computing and Mathematical Sciences department, emphasizes the interdisciplinary nature of modern theory of dynamical systems and control. The curriculum is designed to promote a broad knowledge of mathematical and experimental techniques in dynamical systems theory and control. In addition to taking courses in the CDS option, students must select a focus area (see below).

Master's Degree

Students will be admitted to the option who expect to pursue the Ph.D. degree. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the focus requirements, and receiving a recommendation for awarding of the degree from the candidacy oral examination committee.

Degree of Doctor of Philosophy

Institute requirements for the Ph.D. degree are described in the section on degree requirements. Approximately two years of course work are required, and two or more years are usually needed for preparation of the dissertation.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in control and dynamical systems, the student must, in addition to meeting the general Institute requirements, do the following:

- Complete the following courses: CMS/ACM 104, CMS/ACM 113, CMS/ACM 116; CDS 140 and CDS 212.
- Complete an additional 45 units in CDS or other advanced courses in systems theory, dynamical systems, and/or applied mathematics.
- Complete the focus requirement, consisting of at least 27units in a particular area outside of CDS. Courses taken to satisfy the focus must represent a coherent program of advanced study in the chosen area. Possible areas include biological systems, computer science, environmental science, fluid dynamics, information and communications, networking, robotics, and space systems. The program of study must be approved by the student's counseling committee and the option representative.
- Prepare a research progress report.
- Pass an oral examination on the major topic of the student's research. The oral examination is normally taken no later than the end of the third year of graduate academic residence at the Institute.

Advising and Thesis Supervision. Upon admission, each student is assigned an adviser in the option, who will approve the initial course of study by the student. A preliminary exam given during the first year of study will be used to evaluate the student's preparation for continued study.

The adviser will be replaced by a research adviser and a candidacy committee when the direction of specialization is determined, not later than the beginning of the second year. The candidacy exam is normally taken during the third year of study. The candidacy committee will be the judge of the completion of the engineering focus requirement, necessary before advancement to candidacy. The student's candidacy committee may be reconstituted as the thesis committee after the candidacy exam has been successfully completed.

At the early stages of thesis preparation, the student's thesis committee will meet as needed to advise the student of his or her progress and to deal with any problems that might have arisen.

A final oral examination will be given after the thesis has been formally completed. The thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. Normally this defense will consist of a one-hour public lecture followed by an examination of the thesis by the thesis committee.

Subject Minor

A student majoring in another option at the Institute may elect a subject minor in control and dynamical systems. He or she must obtain approval from the CDS faculty of a course of study containing at least 54 units of courses that are required for the CDS Ph.D. (see Advancement to Candidacy) or advanced courses with a CDS listing

Electrical Engineering

Aims and Scope of the Graduate Program

Award of the Bachelor of Science degree may be followed by graduate study leading to the Master of Science degree in electrical engineering, and the more advanced degrees of Electrical Engineer or Doctor of Philosophy. Because admission to graduate studies in electrical engineering at Caltech is extremely competitive, the Admissions Committee attempts to select those applicants it judges both best qualified and best suited for the graduate program. Applicants should submit Graduate Record Examination scores.

Master's Degree

Normally, the master's degree in electrical engineering is completed in one academic year. The principal criteria for evaluating applicants for the MSEE are the excellence of their preparation for the math- and physics-oriented nature of Caltech's graduate courses, and the judgment of the Admissions Committee on their ability to successfully pursue and benefit from the course program. The Institute does not normally admit an applicant to the master's degree in a field in which the applicant already has a master's degree from another U.S. institution. Financial aid is seldom offered to those who intend to complete their graduate work with a master's degree. A joint B.S./M.S. degree is not available in electrical engineering.

135 units (100 or above) are required as approved by the electrical engineering graduate student adviser. No more than 30 units of pass/fail grades may be counted toward this requirement. Units toward this are not transferable from other schools. At least 54 units of EE letter-graded courses (courses listed or cross-listed as EE) labeled 100 or above and not counting EE 191 or EE 291 are required. EE 105 abc, Electrical Engineering Seminar, is also required. Students are urged to consider including a humanities course in the remaining free electives.

Students who have been admitted to the M.S.-only program must reapply if they are interested in the Ph.D. program.

Degree of Electrical Engineer

The engineer's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for an engineer's degree and receiving a recommendation for its awarding from the candidacy oral examination committee.

Degree of Doctor of Philosophy

As a rule, applicants who wish to undertake research work leading to a degree of Doctor of Philosophy in electrical engineering are admitted initially only for the MSEE. They are, however, evaluated according to additional criteria, the most important of which is the applicant's interest in and potential for research in one of the areas described below. The statement of purpose required as part of the application should clearly address this match. Considerable weight is also given to the opinions expressed in the applicant's letters of recommendation.

During the Ph.D. applicant's master's degree year, evaluation continues. It is based in part on performance in courses and in part on a one-hour oral presentation scheduled early in the second quarter. As the year progresses, the electrical engineering faculty get to know the student, and the student makes contact with the professor in his or her area of research interest. Upon acceptance into a research group, the student begins research work and defers receiving the master's degree until formal admission into the Ph.D. program. Before the end of his or her second academic year of graduate study, the student normally takes the Ph.D. qualifying oral examination. This must, however, be done no later than the end of the third academic year.

Ph.D. applicants who already hold a master's degree in electrical engineering from another U.S. institution may be admitted directly to the Ph.D. program, but must provide sufficient information to obtain advance acceptance into a research group.

Financial aid available to a Ph.D. applicant includes teaching assistantships and fellowships. TA duties consist of grading papers or lab instruction but not classroom lecturing. A fellowship may be supplemented by a teaching assistantship, and either or both include a full tuition scholarship. Tuition scholarships alone are not available. If financial aid is not requested, or if the box on the application form labeled "willing to come without aid" is checked, information on the source of funds for each year of intended graduate study must be included.

Candidacy. To be recommended for candidacy for the doctor's degree, the applicant must satisfy the following requirements (and pass the Ph.D. qualifying oral examination) no later than the end of the third academic year:

- Complete 18 units of research in his or her field of interest.
- Obtain approval of a course of study consisting of at least 135 units of advanced courses in electrical engineering or the related subjects approved by the Ph.D. advisor, with at least 54 units of letter-graded EE courses numbered 100 or above (not counting EE 191 or EE 291). Only up to 27 units in research (e.g., EE 291) may be counted in this total. No more than 30 units of pass/fail grades may be counted toward this requirement. The courses taken to satisfy the math requirement below and courses taken to fulfill the Master of Science degree requirement may be included to satisfy this requirement. Units toward this requirement are not transferable from other schools.
- Pass 27 units of mathematics courses, as approved by the student's research adviser, with letter grade no lower than C.
- Pass a qualifying oral examination covering broadly the major field. Students are strongly encouraged to do this before the end of the second year of residency.

Ph.D. Committee. The Ph.D. qualifying oral exam and the final defense exam are conducted by committees that are set up by the student and approved by the option representative. Members of these Ph.D. committees also serve as second or backup mentors in cases where such additional advising and problem solving are appropriate.

Thesis and Final Examination. The candidate is required to take a final oral examination covering the doctoral thesis and its significance in and relation to his or her major field. This final examination will be given no less than two weeks after the doctoral thesis has been presented in final form, and before its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted.

Advising and Thesis Supervision. Periodic meetings between the advising faculty and the graduate student are an integral part of the Ph.D. program. These meetings should be at sufficiently frequent intervals, as determined by the student and adviser. Students are also encouraged to meet with other members of the Ph.D. committee, the option representative, the executive officer, or Caltech's ombudsperson to discuss problems relating to satisfactory progress.

Subject Minor
A student majoring in another option at the Institute may elect a subject minor in electrical engineering. He or she must obtain approval from the electrical engineering faculty of a course of study containing at least 45 units (over the 100 level) of advanced courses with an EE listing (excluding EE 191 and 291). At least 36 of these should be for letter grades no lower than C. Freshman classes cannot be counted toward this.

Environmental Science and Engineering

Aims and Scope of the Graduate Program
The ESE graduate program trains doctoral students to solve fundamental problems in environmental science and engineering. The problems cut across traditional disciplinary boundaries and span space scales ranging from global to local. Students are trained to acquire a broad base of knowledge of environmental systems, including Earth's atmosphere, oceans, and biosphere. They deepen their knowledge in one or more focus areas, culminating in research leading to a Ph.D. thesis. Reflecting the interdisciplinary nature of research in the ESE program, the program unites faculty from the divisions of Geological and Planetary Sciences, Engineering and Applied Science, and Chemistry and Chemical Engineering.

Admission. Applicants for admission to the ESE program should have undergraduate preparation in science, engineering, or mathematics. Admission is limited to students intending to pursue the Ph.D. degree. All applicants are required to submit scores for the Graduate Record Examination (GRE) General Test. Applicants from non-English-speaking nations are additionally required to submit results for the Test of English as a Foreign Language (TOEFL).

Advising. An academic adviser is appointed for each incoming student to assist in designing his or her academic program. The research adviser is chosen by mutual agreement of the student and adviser during the second year of graduate study, after passing the Ph.D. qualifying examination. The thesis advisory committee (TAC), consisting of four Caltech faculty members including the research adviser, should be constituted and meet with the student soon after the student passes the qualifying examination; thereafter, it should meet with the student annually to review progress and provide guidance and support. Committee membership may be changed if the student's research interests change. The TAC generally serves to recommend the student's advancement to candidacy; it may also serve as the examining committee for the final thesis defense.

Master's Degree
Students enrolled in the Ph.D. program may be awarded a master's degree if they have satisfied the basic Institute requirement of 135 units of work in courses numbered 100 or higher. These courses must include those specifically required in the ESE Ph.D. program.

Degree of Doctor of Philosophy

For the Ph.D. degree, the student must (1) satisfy the course requirements, (2) pass the qualifying examination, (3) advance to candidacy, and (4) complete a thesis and successfully defend it in a final oral examination.

Course Requirements. During their first year, students, in consultation with their academic advisers, must design a program of graduate study that includes a minimum of 135 units of graduate work to be completed before the end of their third year. The course program should take into account the students' individual backgrounds and focus areas, educate them broadly in fundamental questions and methods of contemporary environmental science and engineering, and prepare them for their research.

The course program must include the core courses ESE 101, 102, and 103. Attendance at the weekly research seminars (ESE 104 and 110 abc) is required for first-year students and is expected of all graduate students. All students are expected to have knowledge of methods of applied mathematics and statistics on the level of courses such as Ge 108 and Ge/ESE 118. In cases of unusual preparation, students may petition to substitute a similar but more advanced course for one of the required courses.

Additionally, students are required to take 36 units of elective courses from two of the three groups below:

- Environmental Biology: ESE/Bi 166, ESE/Bi 168, Ge/ESE 170;
- Environmental Chemistry: ESE/Ch 175, ESE/Ch 176, ESE/Ge/Ch 171;
- Environmental Physics: ESE 130-138, Ge/ESE 139, Ge/ESE 150, ESE/ChE 158.

The remaining units of graduate work can be fulfilled by a combination of elective courses in ESE or related disciplines, reading or laboratory courses (ESE 100), and research (ESE 106, 300). Of the total required 135 units, no more than 45 units may be in research. No more than 27 research units may be taken during the first year of graduate study. Exceptions may be granted by petition.

Ph.D. Qualifying Examination. The Ph.D. qualifying examination must be taken during the first term of the student's second year of residency. This examination consists principally of an oral defense of two research propositions, each advised by a different faculty member. Written abstracts must be submitted for both propositions, and one of them must be described in the form of a research report or proposal. The qualifying exam also covers the material of the ESE core courses and of the elective courses the student has taken. In preparation for the qualifying examination, students are encouraged to register for nine units of research (ESE 106) in their second and third terms of residency.

Advancement to Candidacy. Students are recommended to advance to candidacy following the successful completion of a candidacy exam with their Thesis Advisory Committee (TAC). The exam, consisting of both a written Ph.D. thesis proposal and an oral presentation of this plan is required, and must be approved by all TAC members. Advancement to candidacy, including all required course work, should be completed before the end of spring term in the student's third year of residency.

Thesis and Final Examination. Copies of the completed thesis must be provided to the examining committee two weeks before the final oral examination. The final oral examination focuses on the work of the thesis and, according to Institute regulations, must be held at least two weeks before the degree is conferred.

Subject Minor

Students majoring in another option at the Institute may elect a subject minor in environmental science and engineering. They must obtain approval from the ESE Academic Officer for a course of study containing at least 45 units of advanced ESE courses.

Geological and Planetary Sciences

Aims and Scope of the Graduate Program

Students in the Division of Geological and Planetary Sciences study the earth and planets to understand their origin, constitution, and development, and the effect of the resulting physical and chemical characteristics on the history of life, on the environment, and on humanity. Broad training in the fundamental sciences enriched by more specialized course work within the division forms the basis of the educational program. Students are encouraged to work with complex and often incomplete data sets, to undertake research in natural settings such as in the field or at sea, and to use the many modern laboratory facilities available within the division. Programs of study and research are pursued in environmental science and engineering, geobiology, geochemistry, geology, geophysics, and planetary science. The curriculum is flexible so that students with diverse degrees in science and engineering may carry out graduate work within the division. Interdisciplinary studies are encouraged and students may carry out academic and research programs within and between different divisions. The objective is to train students for future employment in academic research, government, and industry.

Admission and Entrance Procedures. Only students who intend to work full-time toward the Doctor of Philosophy (Ph.D.) degree are admitted. The application submission deadline for the GPS Division is January 1. The admission process follows Institute regulations. Applicants are required to submit Graduate Record Examination (GRE) scores for the general test. Individual option requirements for GRE subject tests are specified below:

Environmental Science and Engineering—Not required.
Geobiology—Submit the scores for any subject test.
Geochemistry—Strongly recommended but not required.

Geology—Not required.
Geophysics—Not required.
Planetary Science—Strongly recommended but not required.

Applicants from non-English-speaking nations are required to submit Test of English as a Foreign Language (TOEFL) scores.

Based on their applications and interests, students enter one of the major subject options of the division and are given an academic adviser who is a professorial faculty member associated with the option. The six options are environmental science and engineering, geobiology, geochemistry, geology, geophysics, and planetary science. Students may later change options, but must first obtain approval from the new option. Each student must plan to satisfy the requirements for the Ph.D. degree in one option.

Entering students in the week preceding the beginning of instruction for the first term meet with their option representatives to discuss their preparation in the basic sciences and select a series of courses that will best prepare them for research in their chosen field while meeting the requirements set forth below.

First-year graduate students are encouraged to register for at least nine units of research (Ge 297) in each term of residence. The primary objective is to communicate to the students the excitement of discovery based on original investigations and to provide a broad scope of research aims. An important byproduct can be the formulation of propositions for the Ph.D. qualifying oral examination or orientation toward Ph.D. research.

Advising and Thesis Supervision. The option representative for each incoming student will act as the academic adviser in the first term. An academic adviser will be assigned by the start of second term. This appointed adviser will continue as mentor with broad responsibility for a student's academic welfare throughout the graduate program. During the second year, after passing the qualifying examination, each student should identify a professor as thesis adviser, who will normally provide a graduate research assistantship and the opportunity for continuing research. In consultation with the two faculty advisers, each student then forms a Thesis Advisory Committee (TAC), composed of at least four Caltech professors (chaired by the academic adviser). External scientists closely involved in the student's research may also be appointed. Members of the TAC serve as advisers, counselors, and resources, and its membership may be changed if a student's research interests change.

The thesis advisory committee meets with the student at least once each year for a progress review, and informally whenever the student needs or requests assistance or guidance. In addition, the faculty members in each option have their own systems for annual evaluations of student progress. A few months before completion of the thesis dissertation, the thesis examining committee will be chosen, usually including the members of the thesis advisory committee.

All students are urged to consult with division faculty in the following sequence if they have any problems: thesis and academic advisers, thesis advisory committee, option representative, academic officer, and division chair. If these division personnel cannot resolve a problem, then the student should turn to Institute offices.

Master's Degree

Students enrolled in the Ph.D. program may be awarded a master's degree when they have satisfied the basic Institute requirement of 135 units. These courses must be numbered 100 or higher, and must be part of those used to satisfy the Ph.D. requirement in one of the options of the division. Specifically required are Ge 109 and two courses from the list Ge 101, Ge 102, Ge 103, Ge 104, or ESE 101, ESE 102, ESE 103.

An application for admission to candidacy for an M.S. degree must be submitted in REGIS according to the academic calendar in the *Caltech Catalog* (see pages 4–5).

Doctoral Degree

Division Requirements. For a Ph.D. degree, the student must 1) pass the qualifying oral examination, 2) satisfy course requirements of the division and of an option, and 3) complete a thesis and successfully defend it in a final oral examination. Recommendation to the Dean of Graduate Studies for admission to candidacy occurs after the student has satisfied the first two requirements and has been accepted for thesis research by a division faculty member, who then becomes the student's thesis adviser.

The qualifying examination consists of oral and written defense of two research propositions, supplemented by a written description of one of them. Students are encouraged to consult with various faculty members concerning their ideas on propositions, but the material submitted must represent the work of the student. There must be a different faculty member associated with each of the two propositions. The exam is normally taken early in the first term of the second year of residence and is administered by the qualifying examination committee, which has members from the six options of the division. A more detailed outline of the qualifying examination is available on the division website.

Before the end of the second year, the thesis advisory committee will be selected, as outlined above.

The division encourages students to engage in research early in their graduate careers. Students making normal progress will submit papers to refereed journals that have been approved by a faculty member of the division. The final oral examination for the doctorate by the thesis examining committee will be scheduled no sooner than two weeks following submission of the thesis (approved by the thesis adviser) and, in conformity with Institute regulations, it must be scheduled at least two weeks before the degree is to be conferred.

Candidates are expected to publish the major results of their thesis work. The published papers should have a California Institute of

Technology address. Published papers may be included in the thesis.

By the end of the first academic year (third term): submission by the student of (1) tentative titles of propositions for review by the qualifying examination committee and (2) a list of courses planned to satisfy the Ph.D. requirement, for review by the option.

By the end of the second academic year: (1) passage of oral exam; (2) approval by the option of courses planned to satisfy candidacy requirements; (3) submission of a tentative thesis topic and adviser, and thesis advisory committee.

By the end of the third academic year: (1) satisfactory completion of course requirements; (2) satisfactory completion of other requirements including selection of thesis topic and adviser, and thesis advisory committee; (3) admission to candidacy. A student who has not been admitted to candidacy by the end of the third year will need permission of the academic officer to register.

By the end of the fourth academic year: satisfactory progress toward completion of thesis.

After completing the fifth academic year, the student must formally petition to register for each subsequent year. Financial aid will normally not be extended beyond the sixth year.

The student's program and progress will be reviewed annually by his or her option and by the thesis advisory committee. In cases where, in the opinion of the faculty in the option, the student is clearly not showing adequate progress, they may recommend to the division chair that the student be denied permission to continue in the Ph.D. program based upon their overall assessment of the student's performance.

Basic Division Course Requirement. During the first year, every graduate student will take two of the seven basic introductory courses Ge 101–104 and ESE 101–103, in areas in which the student has not had substantial training. Also required is one term of Ge 109. These should be completed during the first year. Throughout their graduate careers, students are expected to attend departmental seminars and seminar courses led by visiting scientists.

Requirements of the Major Subject Options

Geobiology. In addition to the general Institute and basic division requirements, candidates for the Ph.D. degree in geobiology must successfully complete a minimum of 90 units at the 100 or greater level, including Ge 104; either Bi/Ch 110, Bi/CNS/NB 195, or Ge/ESE 118; and two courses from each of the following three subject menus:

Geology: Ge 106, 112, 114 ab, 124 ab.
Chemistry: Ge/ESE 143, 149, Ge 140 ab, ESE/Ge/Ch 171, 172, ESE/Ch 175, 176.
Biology: ESE/Bi 166, 168, Ge/ESE 170, Bi 117, ESE 103.

Other classes may be substituted for these menu requirements with the approval of the option representative. A student with substantial prior experience in geobiology (e.g., an M.S. degree) may use prior course work to substitute up to 45 of these units with the approval of the geobiology option representative. All students must have a basic knowledge of organic chemistry at the level of Ch 41 a. This requirement may be met by previous course work or through successful completion of this class.

Geochemistry. In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geochemistry are required to demonstrate an understanding of the field through a total of 90 units of course work at the 100 level or higher spread over four of the subdisciplines offered in the option: petrology/mineralogy, isotope geochemistry, cosmochemistry, water chemistry/oceans, atmospheres, biogeochemistry, or advanced chemistry. A student with substantial prior experience in some of the subdisciplines may use prior course work to substitute for up to 45 of these units with the approval of the geochemistry option representative. In the oral candidacy exam, the student will be subject to examination in all four of the chosen subdisciplines. All students must have a basic knowledge of chemistry at the level of Ch 21 and mathematics at the level of Ge 108.

Geology. The geology option requirements are (1) two of Ge 102, 103, 104, or ESE 101, ESE 102, ESE 103, which also satisfy the basic division requirement; (2) 36 units in 100-level science or engineering courses taken outside the GPS division, or in courses cross-listed with other divisions. Ch 21 abc may be included as part of these units, and other courses below the 100 level may be included at the discretion of the option representative. Students with a focus in planetary geology may use 100-level planetary science courses to fill this requirement; (3) 36 units of advanced field geology, in the form of three terms of Ge 121 abc taken from three different instructors; (4) an additional 18 units of 100- or 200-level courses within the GPS division. Courses that cannot be used to satisfy these requirements include research and reading courses, and certain courses constituting basic preparation in the field of geology, such as Ge 106, Ge 112, Ge 114 ab, and Ge 115 ab. A grade of C or better is required for all course work that satisfies these requirements. Knowledge of basic physics, mathematics, and data analysis at the level of Ge 108 and Ge/ESE 118 is required of all Ph.D. candidates in geology. Students entering the geology option with a master's degree in a science or mathematics may be exempt from up to 45 units at the discretion of the option representative.

Geophysics. In addition to general Institute requirements, candidates for the Ph.D degree in geophysics must successfully complete the following: (1) two of the following basic introductory courses: Ge 101, 103, 104, or ESE 101–103, and one term of Ge 109, which also fulfill basic division requirements; (2) either Ae/Ge/ME 160 ab, APh 105 ab, MS 115, or a subject equivalent; (3) three of Ge 161, Ge 162, Ge 163, or Ge 164; (4) Ge 111 ab; (5) the choice between five additional 100- or 200-level science or mathematics courses or a minor in any field at Caltech (for example, computational science and engineering). It is highly recommended that (1)-(4) be fulfilled in the first year and (5) in the second year. A grade of C or better is required for all course work that satisfies these requirements. Knowledge of basic physics, mathematics, and data analysis at the level of Ge 108 and

Ge/ESE 118 is required of all Ph.D. candidates in geophysics. This requirement may be met by previous course work or through successful completion of these classes. Students may substitute another course for a required course if they can demonstrate to an option representative that they have already had the material in the required course.

Planetary Science. In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in planetary science must satisfy the following course requirements: Ge 101, Ge 102, and courses in planetary formation and dynamics (Ge/Ay 133), planetary atmospheres (Ge/ESE 150), planetary interiors (Ge 131), and planetary surfaces (Ge 151). In addition, students shall successfully complete 45 units of 100-level or higher courses in a coherent field of specialization. This requirement may be satisfied by completion of a subject minor or through a set of courses chosen in consultation with and approved by the adviser and the option representative. All candidates are expected to possess knowledge of physics and mathematics at the level of Ph 106 and ACM 95. This requirement may be met by previous course work or through successful completion of these classes.

Subject Minor

A student may, with the approval of the Division of Geological and Planetary Sciences, elect a minor in any one of the major subjects listed above. Such a subject minor will include at least 45 units in courses at the 100 level or higher. Normally, a member of the division faculty will participate in the student's oral thesis defense.

History

The program for a subject minor in history must be approved by the executive officer for the humanities before the admission to candidacy. In addition to meeting general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in history.

History and Philosophy of Science

Graduate students in science, mathematics, or engineering may take a minor in history and philosophy of science (HPS). The graduate minor is devoted to the study of the historical evolution and philosophical underpinnings of the physical and biological sciences. Historical work in the minor includes the origins of experimental practice, the social and institutional contexts of science, the origins and applications of quantitative methods, specific developments since antiquity in physics, biology, and chemistry, as well as biographical and comparative studies. Philosophical research deals with issues in causation, explanation, scientific inference, the foundations of probability and decision theory, philosophy of mind and psychology, philosophy of neuroscience, and scientific fraud and misconduct.

The minor thus fosters the acquisition of broad knowledge about the scientific enterprise and related foundational problems, as well as more detailed analysis of the progress of and philosophical problems in particular branches of science. It is a valuable supplement to a technical degree since it helps equip students to understand the nature of scientific progress and to grapple with the conceptual basis of science and its wider ramifications. Students who successfully complete the HPS minor will be recognized with official credit for the achievement on their transcripts.

Requirements. Graduate students who take an HPS minor are expected to complete Hum/H/HPS 10, HPS 102 ab, HPS/Pl 120, at least three units of HPS 103, and 18 units of additional work in HPS, to be completed by taking courses in HPS/H or HPS/Pl numbered 99 or higher. Students need not complete the requirements for the minor within the first two years of graduate study.

Materials Science

Aims and Scope of the Graduate Program

The graduate program is designed to give students an understanding of general phenomena in synthesis–structure–property relationships in all materials, plus a detailed understanding of phenomena for at least one particular class of materials. After completing the Special Regulations/Ph.D. program, students have pursued careers in teaching and research at colleges and universities, in research for government and industry, in the operation and control of manufacturing processes, and in management and development positions in the materials industry. Students may enter the graduate program in materials science with undergraduate preparation in physics, chemistry, engineering, or materials science.

Students interested in terminating their graduate study at the master's level are not normally admitted. Students in the Ph.D. program are required to complete a set of core courses, pass an oral candidacy examination, complete a thesis describing original research in materials science or a related field, and publicly defend their thesis work.

Preparation for the Graduate Program

Students who have not specialized in materials science as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may also provide a suitable background. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her course of study and research in consultation with members of the faculty and the Materials Science option representative.

Master's Degree

The degree of Master of Science in Materials Science is only awarded to students who do not already have an M.S. degree in Materials Science. The degree will be awarded upon request by students who have fulfilled the requirements. Only in exceptional cases is there admission to the M.S. program as the final degree objective.

Each student is assigned to a member of the faculty who will serve as the student's adviser. The adviser and option representative for materials science will approve his or her course of study. Study for the degree of Master of Science in materials science will ordinarily require three terms of courses. The courses shall be chosen from the list of core courses below, although 27 units of research (MS 200 or equivalent) may be substituted for 27 units of lecture or laboratory courses. Completion of 138 units of these courses within two years with no grade less than a C constitutes the academic requirements for the M.S. degree.

Core Courses

1. MS 131, MS 132, MS 133.
2. APh/MS 105 abc, or ChE/Ch 164 and ChE/Ch 165 and APh/MS 105c
3. Two quarters of courses focused on specific materials, such as APh 114 ab; Ch 120 a; Ch 121 ab; Ch/ChE 147, ChE/Ch 148; Ge 114, Ge 214.
4. Two quarters of courses focused on internal interactions in materials, such as Ph 125 ab, Ch 125 ab or Ae/Ge/ME 160 ab.
5. 18 units of courses comprising either the third terms of the sequences taken in 3 and 4 above, or other courses appropriate for the student's research interests, such as MS 122, MS 125, MS 142, MS/EST 143, MS/ME/MedE 116.
6. Mathematics at the level expected of research in the student's field. This may be satisfied by the courses ACM 100 or ACM 106, AM 125 abc, or ACM 101, or Ph 129 abc, or may be waived at the discretion of the student's adviser and option representative.
7. MS 110 abc (2 units) or APh 110 (4 units) or E 150 abc (2 units), seminar.

Description of the Degree of Doctor of Philosophy (Ph.D.)

As described in more detail below, the doctoral program in Materials Science consists of taking a series of preparatory classes, followed by an oral candidacy exam, a written thesis, and a final oral thesis defense. The goals of this program are to develop competence in a chosen field of specialization; to develop tools with which to assess problems outside the student's field of specialization; to develop sufficient strength in the physical sciences for self-education beyond formal training; and to cultivate the motivation and foresight to become a productive and influential leader. As such, the graduate program in Materials Science is designed to be a doctoral program and students are only admitted into the doctoral program. There is no separate master's program in Materials Science, however, a degree of Master of Science in Materials Science can be awarded upon request by students after the fulfillment of course requirements.

The Ph.D. degree in Materials Science is focused on research. Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project resulting in an original contribution to the field documented by a dissertation is required.

Residency. A minimum of three academic years in residence as a graduate student are required by the Institute, and two or more additional years are usually needed for preparation of the thesis.
Language Requirement. There is no language requirement for the Ph.D. degree.
Minor. No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

Advising and Thesis Supervision
An interim adviser is appointed for each student upon admission to a graduate degree in Materials Science (typically the Materials Science option representative). The interim adviser will serve as the primary mentor until the student finds a research adviser. In the first year (no later than the third term), each student must choose a research adviser who will have primary responsibility for supervising the student's course program and research. The important adviser–advisee relationship requires effort from both parties, and some general expectations are outlined earlier in this section of the catalog. In consultation with their research adviser, the student should then form a Ph.D. thesis advisory committee. This four member committee should include: (i) the student's advisor, and (ii) at least three members of the Caltech professorial faculty. The research adviser and the thesis advisory committee provide the majority of mentoring to the student, providing advice on research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist.

Requirements for Candidacy for the Ph.D. Degree
To be recommended for candidacy for the Ph.D. degree in Materials Science, the student must, in addition to meeting the general Institute requirements, do the following:

a. *Courses.* To continue in the graduate program, the student must maintain a B– average for each term. Advancement to candidacy requires the successful completion of the program listed under "Core Courses" above. Alternatively, if the student has taken equivalent courses elsewhere, he or she may prove competency to the instructor of the equivalent course at the Institute and request a waiver of the required course. With the above course schedule as a guide, students must complete a minimum of 135 units of courses, numbered 101 or above, plus 2 units of MS 110 ab, before presenting themselves for Ph.D. candidacy. The coursework towards the Ph.D. degree in materials science physics is typically completed within the first two years of residency at Caltech.

- All units must be taken for grades and passed with a grade of at least a C, except for courses offered only on a pass/fail basis.
- Only courses in which a student has obtained a grade of C or higher will be counted toward the 135 unit minimum.
- No more than 27 units of research through MS 200 can be counted toward the 135 unit requirement of candidacy.
- Students must complete the degree progress report online.
- Alternate Subjects or Areas
  - o Students entering the program with advanced preparation may choose either to substitute more advanced courses in the topical areas shown or to demonstrate competency.
  - o Students may petition the materials science option representative to accept alternate subjects or areas.
  - o These changes should retain core materials science knowledge, and should represent sufficient breadth.
  - o The approval is not automatic; such petitions must be submitted to the option representative and approved before the student registers for the course.

b. *Oral Candidacy Examination.* This examination should be taken no later than the end of the student's second year of residence. The examination is based on the student's course work, and how it is related to the student's planned research area. The student will be expected to deliver a half-hour oral presentation describing his/her research to date and to answer questions related to this work. This portion of the examination will be followed by more open-ended questions to test general proficiency in the areas of Materials Science. Students who fail the oral examination on their first attempt will be given additional guidelines for further study and an opportunity to retake the examination a second and final time if the committee so recommends. Should a student fail the oral examination a second time, he/she cannot continue with doctoral studies leading to the Ph.D. Upon recommendation of the examining committee, however, the student may be granted a terminal master's degree. The approval of the Materials Science option representative is necessary for registration beyond the fourth year of graduate residence without successfully completing the candidacy exam.

Students who fulfill the requirements above will be recommended for candidacy to the doctoral program and a master's degree (if applicable) in Materials Science.

c. *Research Competence.* The student must have a doctoral research adviser, and must have completed at least 18 units of MS 200.

Ph.D. Thesis Requirements

The candidate is to provide a draft copy of his or her completed thesis to the members of the examining committee (typically the same as the thesis advisory committee) at least two weeks before the final oral examination. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until the thesis is submitted in completed form, i.e., ready for review by the dean, the members of the thesis committee, and the Graduate Office proofreader. Registration is required for the term in which the thesis defense is undertaken, but is not normally allowed beyond the last date of the term. For more information, please see the section entitled "Information for Graduate Students" in the Caltech catalog.

Ph.D. Final Examination

The candidate is required to take a final oral examination covering the doctoral thesis and its significance in and relation to his or her major field. It will consist of a public thesis seminar and an associated oral examination on the thesis and related fields. This examination will be held at least two weeks after the doctoral thesis has been presented in its final form, and prior to its approval.

Registration beyond the Sixth Year of Graduate Residence

The annual approval of the student's thesis advisory committee and option representative is necessary for registration beyond the eighteenth academic term of graduate residence at Caltech.

Subject Minor

A graduate student majoring in another option at the Institute may elect a subject minor in materials science. He or she must obtain approval from the materials science faculty of a course of study containing at least 45 units of advanced courses with a grade of C or higher. Normally a member of the materials science faculty will participate in the candidacy examination in the student's major department.

- Students cannot use courses required by their major option in fulfillment of this requirement.
- Students interested in a minor must receive prior approval from the option representative in materials science, who will review and approve the proposed course of study.
- It is recommended that this course of study include advanced courses spanning different subfields of materials science.

Mathematics

Aims and Scope of the Graduate Program

The principal aim of the graduate program is to develop the student's ability to do original research in mathematics. Independent and critical thinking is fostered by direct contact with faculty members. (An indication of the current research interests of the faculty begins on page 153.) Faculty advisers help students plan their programs of study leading to a Ph.D. in mathematics. Entering students are advised by the director of the Ph.D. program, who assists them in selecting appropriate courses, depending upon their previous studies.

Course Program. The graduate courses are listed in section five. The three core courses—Ma 110 in analysis, Ma 120 in algebra, and Ma 151 in geometry and topology—are required of all graduate students unless excused by the director of the Ph.D. program. Students are expected to complete these core courses in preparation for the qualifying examinations (see below), usually in the first year. (Entering students are allowed to take a qualifying examination in September or October in order to demonstrate knowledge of one or more of the core areas. By passing the examination, they are excused from taking the corresponding course.) In addition, students are required to complete nine quarters of other advanced mathematics courses Ma 111 and above, at least two of which are in discrete mathematics: combinatorics, complexity, and computability, or logic and set theory. Unless these nine course quarters are given pass/fail only, they must be taken for grades. Reading and research do not normally qualify to meet these requirements. Under special circumstances (e.g., finishing the degree in three years), exceptions to these requirements may be granted by the director of the Ph.D. program.

Beginning no later than the second year, students will be expected to begin independent research work and will be strongly encouraged to participate in seminars.

Master's Degree

Entering graduate students are admitted directly to the Ph.D. program, since the Institute does not offer a regular program in mathematics leading to the master's degree. A master's degree may be awarded in exceptional circumstances either as a terminal degree or preliminary to the Ph.D. Sufficiently advanced undergraduates may be admitted to graduate standing to pursue a master's degree simultaneously with the bachelor's program.

The recipient of a master's degree will be expected to take 135 units in advanced mathematics (numbered 110 and higher). Unless the student has placed out of some of them, these must include Math 110, 120, and 151 (the basic courses in analysis, algebra, and geometry). Reading and/or research courses may only be included in this 135 units if approved by the executive officer for mathematics.

The general Institute requirements specify that the recipient of a master's degree must have taken at least 135 units of graduate work as a graduate student at the Institute, including at least 81 units of advanced graduate work in mathematics. This advanced work is interpreted as work with a course number greater than 109 and may include a master's thesis.

Degree of Doctor of Philosophy

Qualifying Examinations. Qualifying examinations in the three core areas—analysis, algebra, and geometry/topology—are offered in October and June. These examinations emphasize mastery of the basic concepts and theorems and the ability to apply them to specific cases. Students are required to take and pass two of the three examinations, and for the one not taken, to complete the corresponding core course with a grade of B or better. Normally, the examination requirements are completed at the end of the first year or the beginning of the second.

Summer Study. Although there are no courses given in the summer, graduate students are expected to carry out studies and research in their chosen area of mathematics. In the summer after the first year, they will work under the guidance of a faculty member to investigate a possible area for their thesis research.

Thesis Adviser. It is expected that by the fall quarter of the second year, students will find a member of the faculty who agrees to serve as their thesis adviser. The progress of all continuing students is assessed by the faculty each fall, and students will consult with their advisers about their progress and planning of their studies and research.

Students receive help and advice not only from their thesis adviser and other faculty mentors, but also whenever needed from the director of the Ph.D. program, and the executive officer. (See also the section with guidelines for graduate student advising on page 297.)

Admission to Candidacy. Before the end of their third year, students are expected to finish the process of applying for admission to candidacy for the Ph.D. degree. This formal step requires completion of the requirements for qualifying examinations and core courses, as well as a satisfactory oral presentation to a committee of faculty members. The presentation will describe both the general area of the student's proposed thesis research and the specific problem or problems to be addressed. A written summary of the presentation, typically 3–10 pages, must be given to the committee members at least one week before the presentation. The student and his or her adviser will arrange the formation of this committee, which will have four members and meet the requirements listed in the subsection Graduate Policies and Proceedure entitled 'Degree of Doctor of Philosophy'.

Thesis and Final Examination. On or before the first Monday in May of the year in which the degree is to be conferred, candidates for the degree of Doctor of Philosophy must deliver copies of their theses to their advisers, to the Graduate Office, and to the members of the committee (of four members that meets the requirements listed in the subsection Graduate Policies and Procedure entitled 'Degree of Doctor of Philosophy') that will conduct the final oral examination on the thesis. The examination must be held at least three weeks before the date on which the degree will be conferred and at least two weeks after the delivery of the copies of the thesis.

Subject Minor
Students majoring in other fields may take a subject minor in mathematics. Minor programs must include 54 units of advanced work approved by a representative of the mathematics department, who will ensure that the work represents a concentrated study in one or more of the main fields of mathematics. A special oral examination in the subject minor will be given soon after completion of the minor program.

Travel Grants
Special funding is available to graduate students to attend conferences and workshops in the United States or abroad (see Bohnenblust Travel Grants on page 315).

Mechanical Engineering

Aims and Scope of the Graduate Program
Mechanical Engineering (ME) research and study are offered through the Department of Mechanical and Civil Engineering (MCE). The degrees of Doctor of Philosophy (Ph.D.) and Master of Science (M.S.) are offered. The M.S. degree is normally only awarded to students who expect to pursue the Ph.D. degree in mechanical engineering and who do not already have an M.S. degree in mechanical engineering. In general, students who intend to work full-time toward the Ph.D. degree as a final degree objective are admitted to the mechanical engineering graduate program.

The aim of the graduate program in mechanical engineering at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, with a strong background in the basic and engineering sciences. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Preparation for the Graduate Program
Students who have not specialized in mechanical engineering as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may provide a suitable background as well. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty.

Master's Degree Description and Requirements
The degree of Master of Science in mechanical engineering is only awarded to students who do not already have an M.S. degree in mechanical engineering. The degree will be awarded upon request by

students who have fulfilled the requirements. Only in exceptional cases is there admission to the M.S. program as the final degree objective.

A minimum of 138 units of courses numbered 100 or above, that meet the required master's program listed below, must be passed with a grade of at least C for completion of the master's degree in mechanical engineering. All units must be taken for grades, except for courses offered only on a pass/fail basis. The M.S. degree in mechanical engineering is typically completed within the first two years of residency at Caltech.

Each student's program must be approved by the adviser and option representative in mechanical and civil engineering before registering for the course.

Required Master's Program

a) Graduate mechanical engineering core (54 units). These units should provide a solid base for the student's engineering interest. The courses should be selected from the core subjects list Areas 1-3 of the mechanical engineering Degree of Doctor of Philosophy Description and Requirements section.
b) Mathematics, engineering, and research electives (54 units). Students who have not taken the equivalent of ACM 100 ab are required to take ACM 100 ab for 24 units. Courses may be taken in Ae, AM, ACM, ME, MS, EE, ESE, APh, CDS, CS, ChE, and CNS. Students are encouraged to take research units, ME 300, up to a maximum of 27.
c) Free electives (27 units). These units may be selected from any course with a number of 100 or greater, except that research units may not be included.
d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

Degree of Doctor of Philosophy Description and Requirements

The Ph.D. degree in mechanical engineering is focused on research. Study and research programs for the Ph.D. degree are individually planned to fit the interests and background of the student. A comprehensive research project resulting in an original contribution to the field documented by a dissertation is required. A minimum of three academic years in residence as a graduate student are required by the Institute, and two or more additional years are usually needed for preparation of the thesis.

Advising and Thesis Supervision. An interim adviser is appointed for each student upon admission to a graduate degree in mechanical engineering. The interim adviser will serve as the primary mentor until the student finds a research adviser. It is the responsibility of the student to find an academic and research adviser within three terms of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee within four terms of graduate residence at Caltech. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering. The committee shall meet as requested by the student. Further, the committee shall meet annually to review progress and to approve the registration of the student beyond the fifth year of graduate residence at Caltech.

The adviser and the thesis advisory committee provide the majority of mentoring to the student. In addition, the option representative and other members of the faculty are always available to provide advice and mentoring on any aspect of research, progress toward the Ph.D., future careers, and other aspects of life in graduate school and as a professional scientist.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in mechanical engineering, the student must, in addition to meeting the general Institute requirements, do the following:

- Obtain the agreement of a professorial faculty member to serve as his or her academic and research adviser before the end of the third term of graduate residence at Caltech. In consultation with the adviser, the student must form a Ph.D. thesis advisory committee before the end of the fourth term. This committee shall consist of at least three members of the Caltech professorial faculty, with at least two members from the faculty in mechanical and civil engineering.
- Pass both subject and research components of the oral candidacy examination before the end of the eighth term of graduate academic residence at Caltech. If the student has chosen a subject minor, an examination on the subject of that program may be included at the request of the discipline offering the subject minor.
- Complete a minimum of 195 units of courses numbered 101 or above, that meet the required Ph.D. program listed below. All units must be taken for grades and passed with a grade of at least a C, except for courses offered only on a pass/fail basis. The course work towards the Ph.D. degree in mechanical engineering is typically completed within the first three years of residency at Caltech.

Required Ph.D. Program

a) Mechanical engineering core subjects (54 units). Course workin three core mechanical engineering subjects, 18 units each of the three subjects, spanning at least two broad areas listed below. Most students prepare for the subject candidacy exam by taking the recommended set of courses listed below in Areas 1-3, plus math. These 54 units may also be used in the student's program for the master's degree. Examples of suitable courses are given in parentheses.

Core ME Subjects
Area 1
Fluid Mechanics (Ae/APh/CE/ME 101 abc)
Mechanics of Structures and Solids (Ae/AM/CE/ME 102 abc)
Continuum Mechanics of Solids and Fluids (Ae/Ge/ME 160 ab)

Area 2
Thermodynamics and Statistical Mechanics (ME 117, ME 118, APh 105, Ch/ChE 164, Ch 166)
Heat and Mass Transfer (ME 119 ab)
Combustion (Ae/ME 120 ab)

Area 3
Dynamical Systems (AM/CE 151 ab or CDS 140 & CDS 240)
Mechanical Systems and Design (ME 115 ab)
Controls (CDS 110, CDS 112, CDS 212)

The student may petition the mechanical and civil engineering Option Representative to accept alternate subjects or areas. These changes should retain core mechanical engineering knowledge, should not be a sub-specialty of one of the listed areas, and should represent sufficient breadth. The approval is not automatic; such petitions are submitted rarely and many have been denied in the past. The petition must be submitted to the option representative and approved before the student registers for the course.

b) Additional engineering or science courses, with a course number 101 or above (54 units). Pass with a grade of at least C, courses that pertain to the student's specialty and are approved by the thesis advisory committee.
c) Advanced mathematics or applied mathematics (27 units). Pass with a grade of at least C, chosen in consultation with the adviser from the following list: ACM 101 or higher, CDS 140, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.
d) Graduate engineering seminar (6 units). Pass six terms of AM/CE/ME 150 abc, within the twelve terms, 3 years, in residence at Caltech.
e) Research (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

The requirement of a minimum grade of C will be waived for an advanced course which is offered only pass/fail. The faculty will evaluate the student's research progress, class performance, adviser's input, and oral candidacy exam results to determine whether a student will be admitted to or be able to maintain candidacy for the Ph.D. degree.

Registration Beyond the Sixth Year of Graduate Residence. The annual approval of the Ph.D. dissertation supervision committee is necessary for registration beyond the twenty-fourth academic term of graduate residence at Caltech.

Thesis and Final Examination. The thesis examination will be given after the thesis has been formally completed. This examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. The format of the examination can be chosen from the following two options, by the student, in consultation with their research advisor: (i) a public seminar presented by the candidate, with an open question period, followed by a private examination by the examining committee or (ii) a private presentation to the examining committee followed by the examination, with a public seminar on another date. The examining committee shall consist of a minimum of four voting members, three of whom must be Caltech faculty; two members must be from MCE. The thesis defense committee shall be chaired by a committee member who is an MCE Caltech professorial faculty member and not the student's adviser.

Subject Minor

A student majoring in another branch of engineering or another division of the Institute may, with the approval of the faculty in mechanical engineering and the faculty in his or her major field, elect mechanical engineering as a subject minor. The program of courses must differ markedly from the major subject of study or research, and must consist of at least 54 units of advanced courses (101 or above) approved by the faculty in mechanical and civil engineering.

Medical Engineering

Aims and Scope of the Graduate Program

The Medical Engineering option at Caltech is designed for students with an engineering background who are interested in applications of micro-/nanoscale science and technology in medicine, which forms the core of Caltech's multidisciplinary Medical Engineering. The program's goal is to close the gap between engineering and medicine. Our Medical Engineering research and education leverage Caltech's strengths in engineering, applied science, and other fundamental fields, to apply emerging technological advances to medicine, and to create innovative diagnostic, monitoring, and therapeutic systems. Our major tracks of research are: micro/nano medical technologies and devices, medical nanoelectronics, biomedical materials and biomechanics, fluidics and bioinspired design, and medical imaging and sensing.

Master's Degree in Medical Engineering

Students are not normally admitted to work towards the M.S. degree. However, the M.S. degree may be awarded to a student along the way toward a PhD degree, provided Institute and Option requirements are met. The Option requirements for the MS degree are the same as those for the PhD degree except that the MS degree does not require research units, qualifying exam, candidacy exam, and thesis defense. In general, the degree is not conferred before the end of the first year of residence.

Degree of Doctor of Philosophy in Medical Engineering

(I) *Admission to Candidacy.* To be recommended for candidacy for the Ph.D. program in Medical Engineering, each student must, in addition to meeting the general Institute requirements of a minimum of 135 units of graduate work, complete all the following requirements:

- Complete 27 units of advanced courses (i.e., 100 level or above), with a grade B or better, in mathematics as arranged with his/her adviser. Math courses that are recommended include, but are not limited to: ACM 100 ab, ACM 101, ACM 104, ACM 105, ACM 106 abc, GE/ESE 118, ACM 201 ab, ACM 210 ab, ACM/EE/CMS 116, AM 125abc, and Ma 112 ab.
- Complete the three-term seminar sequence, MedE 100 abc (1 unit), with a pass grade.
- Complete MedE 101 (9 units) with a pass grade.
- Complete the two-term core MedE/Ae/BE 243 Medical Engineering course sequence, MedE 201 ab (18 units), with a B grade or better.
- Complete MedE/BE/Ae 243 (9 units), with a B grade or better.
- Complete EE111 (9 units), with a B grade or better.
- Complete at least 27 units of MedE 291 individual research.
- Complete minimally an additional 42 units of advanced courses (100 level or higher and, if available, grades only) in the following 8 topical areas as arranged with the student's adviser. Courses that are recommended but not limited to, include:

  (1) Fundamental and Mathematically Oriented Engineering: APh/EE 130 (EM), CDS 101, CDS 110, CDS 140, ChE/BE/MedE 188, ChE 103 abc, EE112, EE/Ma 126ab, EE 151, EE160, EE 161, MS 115, ME 115 ab, ME 117, ME 118, ME 119 ab.
  (2) Solid Mechanics: Ae/AM/CE/ME 102 abc, Ae 160, AM/CE 151 ab, MS/ME/MedE 162.
  (3) Fluid Mechanics: Ae/APh/CE/ME 101 abc, Ae 160, Ae/BE 242, ChE/BE/MedE 112.
  (4) Biology and Physiology: BE 150, BE 151, BE/Bi 152, BE 159, Bi/Ch 110, Bi/Ch 113, Bi 122, Bi 129, Bi 145, Bi/CNS/NB 150, Bi/CNS 162, CNS/Bi/Ph/CS/NB 187.
  (5) Biomaterials, Biomechanics, and Bioinspired Design: Ae/BE 242, BE 141, BE159, Ch/ChE 147, MS/ME/MedE 162, ME/MS 260, MS 115.
  (6) Medical Photonics and Imaging: APh/EE 130, APh/EE 131, APh/EE 132, Bi/BE 177, Bi/BE 227, ChE 114,

EE/MedE 115, EE 151, EE/BE/MedE 166, MedE 205.
(7) BioSensing: APh/EE 130, APh/EE 131, APh/EE 132, EE/MedE 114ab, EE/MedE 115, EE 151, EE 161, EE BE/MedE 166, EE/APh 180.
(8) Medical Technologies and Devices: APh 109, APh 114abc, APh/EE 130, APh/EE 131, APh/EE 132, BE/ EE/MedE 189, ChE/BE/MedE 112., ChE 115, E/ME/ MedE105ab, EE 12, EE/MedE 114 ab, EE/MedE 124, EE 151, EE 161, EE/APh 180, EE/BE/MedE 185, EE/ MedE 187, MedE 205.

- Pass an oral qualifying examination, arranged by the Option, on three major subjects before the beginning of the second academic year. Any delay of taking the exam must be preapproved by the option representative. Each student should consult his/her adviser and/or the option representative to choose the three major subjects. The three subjects of the exam should include (1) engineering math, (2) the major researchtopical area, and (3) another related topical area. Students should take at least 27 units of advanced courses on each of the three exam subjects. If the student has a subject minor, examination on the minor subject may be included at the request of the discipline offering the minor and with the approval of his/her adviser. Note that the program is designed for the students to have multidisciplinary background.
- Pass an oral candidacy examination on the subject of the Ph.D. research before the end of the third academic year of residency. The Ph.D. oral candidacy exam is conducted by a committee of minimum four members that is set up by the student and approved by the option representative. This examination will be a test of the candidate's preparation and knowledge to conduct research in his or her specialized doctoral research area.
(2) Thesis and Final Examination.
The Ph.D. final thesis defense exam is conducted by a committee that are set up by the student and approved by the option representative. The committee should be made of minimum 5 members and the majority must be MedE faculty. This final examination will be given no less than two weeks after the doctoral thesis has been presented in final form, and before its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted. This thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized doctoral research area.

Subject Minor

A subject minor is not required, but recommended, for the Ph.D. degree in Medical Engineering. However, credits from the subject minor can not be double-counted for the core program. Students may choose their original engineering disciplines as their minor subjects. Students are not allowed to choose Medical Engineering as a subject minor.

Neurobiology

Aims and Scope of the Graduate Program

Neurobiology—the study of the nervous system—is a highly integrative science. The modern neurobiologist must be conversant with concepts from molecular biology, cell and developmental biology, systems neuroscience, animal behavior, and mathematical modeling. The aim of the graduate program is to expose each student to this breadth of the discipline. To accomplish this, we offer a first-year curriculum with requirements in specified areas, along with a core course that spans many subjects. Students enter neurobiology from many different disciplines, ranging from particle physics to physiology to psychology. Accordingly, each Ph.D. student is paired with a first-year advisor, so the course selections can best complement the student's background. In later years, the student's focus is on original research in a chosen specialty. Our goal is that students will graduate with specific research accomplishments and the broad understanding required to chart their subsequent forays in brain science.

Admission

Applicants are expected to have studied college-level mathematics, physics, chemistry, and biology. They should also have experience in independent research. Coursework in neurobiology and experience in scientific computing are helpful, but not required. Whenever possible, applicants will be interviewed on campus before final admission decisions are made.

Master's Degree

The option does not admit students for work toward the Master's degree. A terminal M.S. may be awarded in exceptional circumstances.

Degree of Doctor of Philosophy

First-year advisor

Each incoming student is paired with an academic advisor during the first year. This mentor will guide the student in course selection and other decisions, taking the student's background into account. Where possible, this advisor will not be one of the prospective rotation supervisors.

Rotations

First-year students carry out three laboratory rotations, each lasting one quarter. At least two of these should be with faculty participating in the option. By June 30 of the first year, students choose a Ph.D. advisor.

Formal Classes

Students take at least 6 quarter courses (54 units) as follows:

1. Bi/CNS/NB 164, Tools of Neurobiology
2. One course in molecular, cellular, developmental neurobiology;
3. One course in circuits, systems, behavioral biology;
4. One course in mathematical methods (depending on student background);
5. Two electives.

For a list of courses in subject areas 1-3, see the option website. In addition, students take a short course on responsible conduct of research (Bi 252). All courses must be taken for a grade unless only offered pass/fail.

Teaching
Students serve as teaching assistants for three terms.

Admission to Candidacy
To qualify for candidacy, the student must first demonstrate broad competence by passing each of the first-year courses with a grade of B or higher. Failure here can be remedied by successful second-year coursework. By June of the second year, the student must also defend a thesis proposal in an oral exam before a qualifying exam committee of at least 3 faculty. This exam will also cover general knowledge in the relevant field. With special permission, the oral exam may be retaken once before the end of winter quarter of the third year. Students that do not advance to candidacy by the end of the third year may not continue in the program.

Thesis Advisory Committee
Once admitted to candidacy, the student chooses a thesis advisory committee of at least 3 faculty. This committee serves as a source of advice independent of the Ph.D. advisor throughout the student's tenure. Each year, before the end of June, the student delivers a written progress report, followed by a meeting with the thesis advisory committee.

Thesis Examination Committee
This committee is usually the same as the thesis advisory committee, but this need not be the case. The final oral examination covers principally the work of the thesis, and according to Institute regulations must be held at least two weeks before the degree is conferred.

Physics

Aims and Scope of the Graduate Program
The physics option offers a program leading to the degree of Doctor of Philosophy. This program prepares students for careers in scientific research or research combined with teaching, and so its most important part is independent research. Courses are offered that give a broad treatment of both fundamental physics and specialized physics research topics. These are intended both to help a beginning graduate student prepare for research and to broaden an advanced student's knowledge of physics. Caltech research opportunities include elementary particle physics, nuclear physics, cosmic-ray, gamma-ray, and X-ray astronomy, submillimeter astronomy, condensed-matter physics, atomic/molecular/optical physics, quantum optics, applied physics, gravitational physics, cosmology, astrophysics, mathematical physics, biophysics, and theoretical physics.

A Master of Science degree may be awarded upon completion of a program of courses. Students are not normally admitted to work toward the M.S. in physics unless they are also working toward a Ph.D.

Admission. The application submission deadline for Physics is December 15. The admission process follows Institute regulations. Applicants are required to submit Graduate Record Examination (GRE) scores for the general test and scores for the Advanced Physics subject test.

Placement Examinations. Students admitted to work for an advanced degree in physics are required to take placement examinations, typically given the Monday of general orientation week before the student's first term of graduate study. These informal exams are used as a guide in selecting the proper course of study. The exams cover material in classical mechanics, electromagnetism, quantum mechanics, statistical mechanics, and mathematical physics. In general, they will be designed to test whether the student possesses an understanding of general principles and the ability to apply these to concrete problems, rather than detailed informational knowledge. The results of the placement exams are not formally recorded as a part of the student's record. In cases in which there is a clear basis for ascertaining the status of the entering graduate student, the placement exams may be waived.

Master's Degree

A Master of Science degree in physics will be awarded, upon request, to physics Ph.D. students who have completed the oral and written candidacy examinations. Alternatively, a master's degree will be awarded to any Caltech graduate student in good standing upon satisfactory completion of a program approved by the option representative that fulfills the following requirements:

Ph 125 abc (If this course, or its equivalent, was taken as part of an undergraduate program, it may be replaced by 27 units of any quantum-mechanics–based course.)	27 units
Physics electives These must be selected from Ph 103, Ph 105, Ph 118, Ph 127, Ph 129, Ph 135, Ph 136, or physics courses numbered 200 or above.	81 units
Other electives These must be graduate courses from physics or any other option, including the humanities.	27 units

Substitutions of other graduate courses in place of the above requirements must be approved by the option representative.

In exceptional cases, undergraduate students may receive concurrent B.S./M.S. degrees if the above requirements are met in addition to the relevant B.S. requirements, upon approval from the Physics Graduate Committee, the graduate admissions committee, and the physics executive officer. Such students must produce a detailed petition demonstrating accomplishments that would warrant normal admission to the physics graduate program.

Degree of Doctor of Philosophy

In addition to the general Institute requirements for a Ph.D., the particular requirements for a doctorate in physics include admission to candidacy as described below, writing a thesis that describes the results of independent research, and passing a final oral examination based on this thesis and research. Physics graduate students may exercise the pass/fail option on any and all courses taken.

Admission to Candidacy. To be recommended for Ph.D. candidacy, a student must pass two terms of Physics Seminar (Ph 242), pass written candidacy examinations covering basic physics, satisfy the Advanced Physics requirements described below, and pass an oral candidacy examination. These requirements are designed to ensure that students have an adequate preparation in the basic tools of physics, as well as a broad general knowledge of advanced physics.

Basic Physics Requirement. To be admitted to candidacy, physics students must demonstrate proficiency in all areas of basic physics, including classical mechanics (including continuum mechanics), electricity and magnetism, quantum mechanics, statistical physics, optics, basic mathematical methods of physics, and the physical origin of everyday phenomena. A solid understanding of these fundamental areas of physics is considered essential, so proficiency will be tested by written candidacy examinations.

No specific course work is required for the basic physics requirement, but some students may benefit from taking several of the basic graduate courses, such as Ph 106, Ph 125, and Ph 127. A syllabus describing the exam contents will be available, and students are encouraged to study independently for the exams, rather than taking a heavy load of basic physics courses.

The written exams are typically offered in June and in October, and the separate exams may be taken at different times. This flexible scheduling of the written exams allows students to prepare for the exams while simultaneously learning about research areas, either through advanced courses, reading courses, or participation in a research group.

Advanced Physics Requirement. In addition to demonstrating a proficiency in basic physics, students must also establish a broad understanding of modern physics through study in six of the following eight areas of advanced physics:

1. elementary particle physics
2. nuclear physics
3. atomic/molecular/optical physics
4. condensed-matter physics

5. gravitational physics
6. astrophysics
7. mathematical physics
8. interdisciplinary physics (e.g., biophysics, applied physics, chemical physics)

Each area is meant to be covered by the equivalent of a one-term course, and a list of course substitutions for each of the areas can be found at the physics department website. Other courses may be substituted with permission of the Physics Graduate Committee.

Oral Candidacy Exam. This exam is primarily a test of the candidate's suitability for research in his or her chosen field. The chair of the examination committee will be the professor the student plans to do research with, and normally the student will have already begun research (Ph 172 or Ph 173) on a definite topic with that professor. The examination will cover the student's research work and its relation to the general field of specialization. Before being allowed to take this exam, a student must have satisfied all the other requirements for admission to candidacy.

Research Requirements. There are no specific research requirements, but in general a substantial effort is required to master the techniques in a given field and carry out a significant piece of original research. Students are strongly advised to start doing part-time research as soon as possible, and to carry it on in parallel with formal course work, taking reading and research units (Ph 171–173) prior to being admitted to candidacy. Typically, students continue graduate study and research for about two years after admission to candidacy.

Scheduling. Although students are encouraged to begin doing research soon after arriving at Caltech, they should also try to complete the requirements for candidacy as quickly as possible before focusing completely on a particular research area. Thus Ph 242 should be taken by all students in their first year of graduate study. The written candidacy exams should be attempted by the end of a student's first year of study, and be passed by the end of the second year. The Advanced Physics requirements should also be completed by the end of the second year, but may be extended into the third year depending on the availability of specific courses. If these deadlines are not met, a student must petition the Physics Graduate Committee before registration for subsequent terms will be allowed.

Advising and Thesis Supervision. After taking the placement exams described above, physics graduate students meet with the chair of the admissions committee to decide on a first-year course schedule. At this time it is appropriate for students, especially those admitted with GRAs, to consult with the admissions chair, the option representative, the executive officer, and/or individual faculty members to select a tentative research group, if this hasn't already occurred over the summer. At any time, a student may consult with the option representative concerning such matters as advising and switching research groups. When the student is ready to form his or her candidacy committee, this is done in consultation with the executive officer. This committee, besides examining the student's knowledge of his or her chosen field, will consider the appropriateness and scope of the proposed thesis research. Supervision of the thesis research is the responsibility of the thesis adviser, and the student should maintain close contact with his or her adviser. In some circumstances, such as interdisciplinary work with an adviser from another department, a special committee may be formed to follow the progress of the research as well.

The Minor. A minor is not required, but a student may elect to pursue a minor in another option.

Language Requirements. There are no language requirements for a Ph.D. in physics.

Thesis and Final Examination. A final oral examination will be given not less than two weeks after the thesis has been presented in final form. This examination will cover the thesis topic and its relation to the general body of knowledge of physics. The candidate is responsible for completing the thesis early enough to allow the fulfillment of all division and Institute requirements, with due regard for possible scheduling conflicts.

Subject Minor

Students desiring a subject minor in physics should discuss their proposed program with the chair of the Physics Graduate Committee. Forty-five units are required for approval of a subject minor in physics. Physics courses with numbers over 100 will be allowed for the subject minor. At least 18 of the 45 units must be chosen from the physics electives list (see list under *Master's Degree* in this section), excluding Ph 129 and any specific courses in physics required for the student's major program. An oral exam may be required by the Physics Graduate Committee. This exam will include both academic topics and topics on current physics research areas. The oral exam may be waived if at least one term of Ph 242 has been taken successfully, or if all 45 units are in letter-graded (*not* pass/fail) courses.

Social Science

Aims and Scope of the Graduate Program

The Caltech Ph.D. program in social science prepares students for an academic career in economics and political science. It is designed to produce scholars who are well grounded in the theoretical perspectives, the quantitative techniques, and the experimental methods of economics and political science.

Master's Degree

Students who are enrolled in the Social Science Ph.D. program may earn a M.S. degree after successful completion of 36 units of course work, approved at least with a B grade, in addition to completing the coursework required for the first year of the PhD program.

Admission. Admission to the Caltech Ph.D. program is based on prospective students' academic records, research interests, GRE scores, and letters of recommendation. Students who are not native English speakers are also required to submit scores from the TOEFL exam.

Course Program.

First year. The first-year curriculum consists of the following three-quarter course sequences: Analytical Foundations in Social Science (SS 201 abc); Political Theory (SS 202 abc); Foundations of Economics (SS 205 abc) and Econometrics (SS 222 abc). Each class must be completed with a grade of B or better. Students are also required to audit one quarter of an introductory social science class, either Introduction to Economics (Ec 11) or Introduction to Political Science (PS 12).

Before the start of the second year, students are required to take a written preliminary examination which has four components, each corresponding to one of the first-year course sequences (SS 201, SS 202, SS 205, and SS 222). The grades given are Honors, Pass, and Fail. Students must achieve at least a Pass in all four parts. The Social Science faculty will review the student's performance on the exam, and progress, to date. If it is not satisfactory, they may terminate the student from the program by the beginning of the second year.

Second year. Second-year courses provide additional training in various subfields of social science. Students are expected to take at least two second-year course sequences. Such course sequences include Foundations of Political Economy (SS 210 abc), Advanced Economic Theory (SS 211 abc), Applications of Microeconomic Theory (SS 212 abc), Identification Problems in the Social Sciences (SS 227 abc), American Politics (SS 231 abc), and Experimental Methods of Political Economy (SS 260 abc). Courses that are offered frequently, but not necessarily every year, include Financial Economics (SS 213 abc) and Advanced Topics on Econometric Theory (SS 223 abc). Students may fulfill the second-year sequence requirement by taking a sequence of courses in mathematics, such as Classical Analysis (Ma 108), Analysis (Ma 110), Probability Theory (Ma 144), or Convex Analysis and Economics (Ec 181).

Second-year students must enroll in 36 units of courses during the Fall and Winter; and 18 units during the Spring. In the Spring, students should enroll in SS 300, a seminar devoted to work on their second-year paper, and the Graduate Social Science Writing Seminar (SS 281). SS 300 is taken on a pass/fail basis. All other classes offered for grades must be taken on grades, and completed with a grade of B or better. Students may take independent reading and study courses, but during the second year such courses do not count toward the above requirements.

Third year. Beginning in their third year, and in all subsequent years, all students should also enroll in the 3-unit graduate student seminar (SS282) every quarter. Every student must make a presentatation in this class at least once a year. Students should enroll in Research in Social Science (SS300) for the units remaining to reach 36.

Fourth and fifth year. Students need to register for 33 units of SS 300 and 3 units of the graduate student seminar SS 282.

Progress in the program, and advancement to candidacy
In addition to the coursework and examinations described above, students must enroll in 36 units per quarter, and complete the following requirements.

By February 1 of their second year, students should choose a second-year paper adviser. The adviser must be a member of the social science faculty at Caltech. The DGS will appoint a second faculty reviewer, and together with the second-year paper adviser, they will monitor and evaluate progress on the second-year paper.

By the end of the second year, students must submit a research paper to the DGS and their two-faculty committee. The paper cannot be co-authored. If the two faculty reviewers find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will review the student's paper. If they decide that the paper is not satisfactory, they may terminate the student from the program.

Third-year students must write a research paper and present it to the faculty by the end of the third quarter. The paper cannot be co-authored, but should be worked on in consultation with and under the direction of the student's adviser. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience.

After completion of the third-year paper presentation, the social science faculty evaluates the student's overall performance and research potential. This review is based primarily upon the third-year paper, but the faculty also verifies that the student has satisfactorily completed all previous requirements.

If this evaluation is favorable, the student is admitted to candidacy for the Ph.D. If the faculty evaluation is unfavorable, the student may be terminated from the program.

Organization of Thesis Committee.
By October 1 of their third year, students should have selected a primary adviser. The adviser shall serve as chair of the student's dissertation committee, and must be a member of the social science faculty at Caltech. It is possible to change advisers if a student's research interests change. Students, in consultation with their advisor, must select two additional committee members after the student has advanced to candidacy (normally by the beginning of their fourth year). One member may be from outside the social science faculty, but such choices must be approved by the DGS. After a student advances to candidacy, the division chairperson shall select a fourth member of the committee with an eye to representing the diverse interests of the social science faculty.

Degree of Doctor of Philosophy
By November 1 of their fourth year, students must complete a dis-

sertation prospectus that outlines the proposed dissertation work, and presents a tentative schedule detailing when the components of the dissertation are to be completed. The prospectus must clearly identify a project, or dissertation components, that should culminate in a job market paper at the beginning of the student's fifth year (August before the start of the fifth year, in the case of students who seek a position in political science). The prospectus must be approved by the dissertation committee by November 1, and communicated by the principal adviser to the DGS.

By May 1 of the fourth year, all students are required to convene a thesis prospectus seminar with their adviser and other committee members. In this seminar, they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. The seminar must be based on the student's planned job market paper, and a draft of this paper must accompany the proposal. Students and their committee should reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation.

After the dissertation has been completed, students, in consultation with their adviser, must schedule an oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research.

Section Five

Courses

Courses numbered below 100 are taken primarily by undergraduate students. Those numbered from 100 to 199 are taken by both undergraduates and graduates, and those numbered 200 and above are taken primarily by graduate students.

The school year is divided into three terms. The number of units assigned in any term to any subject represents the number of hours spent in class, in laboratory, and estimated to be spent in preparation per week. In the following schedules, figures in parentheses denote hours in class (first figure), hours in laboratory (second figure), and hours of outside preparation (third figure).

At the end of the seventh week of each term, a list of courses to be offered the following term is published by the Registrar's Office. On the day of registration (see Academic Calendar), an updated and revised course schedule is published announcing the courses, class hours, and room assignments for the term. Students may not schedule two courses taught at the same time.

Abbreviations

Ae	Aerospace
An	Anthropology
ACM	Applied and Computational Mathematics
AM	Applied Mechanics
APh	Applied Physics
Art	Art History
Ay	Astrophysics
BMB	Biochemistry and Molecular Biophysics
BE	Bioengineering
Bi	Biology
BEM	Business Economics and Management
ChE	Chemical Engineering
Ch	Chemistry
CE	Civil Engineering
CNS	Computation and Neural Systems
CS	Computer Science
CMS	Computing and Mathematical Sciences
CDS	Control and Dynamical Systems
Ec	Economics
EE	Electrical Engineering
EST	Energy Science and Technology
E	Engineering
En	English
ESL	English As a Second Language
ESE	Environmental Science and Engineering
F	Film
FS	Freshman Seminars
Ge	Geological and Planetary Sciences
H	History
HPS	History and Philosophy of Science
Hum	Humanities
ISP	Interdisciplinary Studies Program Program
IST	Information Science and Technology
L	Languages
Law	Law
MS	Materials Science
Ma	Mathematics
ME	Mechanical Engineering
MedE	Medical Engineering
Mu	Music
NB	Neurobiology
PA	Performance and Activities
Pl	Philosophy
PE	Physical Education
Ph	Physics
PS	Political Science
Psy	Psychology
SS	Social Science
Wr	Writing

AEROSPACE

Ae 100. Research in Aerospace. *Units to be arranged in accordance with work accomplished.* Open to suitably qualified undergraduates and first-year graduate students under the direction of the staff. Credit is based on the satisfactory completion of a substantive research report, which must be approved by the Ae 100 adviser and by the option representative.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 or ME 11 abc, and ME 12 or equivalent, ACM 95/100 or equivalent (may be taken concurrently).* Fundamentals of fluid mechanics. Microscopic and macroscopic properties of liquids and gases; the continuum hypothesis; review of thermodynamics; general equations of motion; kinematics; stresses; constitutive relations; vorticity, circulation; Bernoulli's equation; potential flow; thin-airfoil theory; surface gravity waves; buoyancy-driven flows; rotating flows; viscous creeping flow; viscous boundary layers; introduction to stability and turbulence; quasi one-dimensional compressible flow; shock waves; unsteady compressible flow; and acoustics. Instructor: Pullin, Austin.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisite: ME 35 abc or equivalent.* Static and dynamic stress analysis. Two- and three-dimensional theory of stressed elastic solids. Analysis of structural elements with applications in a variety of fields. Variational theorems and approximate solutions, finite elements. A variety of special topics will be discussed in the third term such as, but not limited to, elastic stability, wave propagation, and introductory fracture mechanics. Instructors: Kochmann, Ravichandran, Bhattacharya.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6) first term; (0-6-3) second, third terms. Prerequisites: ACM 95/100 ab or equivalent (may be taken concurrently), Ae/APh/CE/ME 101 abc or equivalent (may be taken concurrently).* Lectures on experiment design and implementation. Measurement methods, transducer fundamentals, instrumentation, optical systems, signal processing, noise theory, analog and digital electronic fundamentals, with data acquisition and processing systems. Experiments (second and third terms) in solid and fluid mechanics with emphasis on current research methods. Instructor: McKeon.

Ae 105 abc. Aerospace Engineering. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 11 abc and ME 12 abc or equivalent.* Part a: Introduction to spacecraft systems and subsystems, mission design, fundamentals of orbital and rocket mechanics, launch vehicles and space environments; JPL-assisted design exercise; spacecraft mechanical, structural, and thermal design; numerical modeling, test validation. Part b: Introduction to guidance, navigation, and control (GNC), measurement systems, Kalman filtering, system analysis, simulation, statistical error analysis, case studies of GNC applications; preliminary discussion and setup for team project leading to system requirements review. Part c: Team project leading to preliminary design review and critical design review. Instructors: Davis, Freeman, Scharf.

CE/Ae/AM 108 ab. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

Ae 115 ab. Spacecraft Navigation. *9 units (3-0-6); first, second terms. Prerequisite: CDS 110 a.* This course will survey all aspects of modern spacecraft navigation, including astrodynamics, tracking systems for both low-Earth and deep-space applications (including the Global Positioning System and the Deep Space Network observables), and the statistical orbit determination problem (in both the batch and sequential Kalman filter implementations). The course will describe some of the scientific applications directly derived from precision orbital knowledge, such as planetary gravity field and topography modeling. Numerous examples drawn from actual missions as navigated at JPL will be discussed. Not offered 2015–16.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. *12 units (3-0-9), second term.* For course description, see Applied Physics.

Ae/ME 118. Classical Thermodynamics. *9 units (3-0-6); first term. Prerequisites: ME 11 abc, ME 12, or equivalent.* Fundamentals of classical thermodynamics. Basic postulates and laws of thermodynamics, work and heat, entropy and available work, and thermal systems. Equations of state, compressibility functions, and the Law of Corresponding States. Thermodynamic potentials, chemical and phase equilibrium, phase transitions, and thermodynamic properties of solids, liquids, and gases. Examples will be drawn from fluid dynamics, solid mechanics, and thermal science applications. Not offered 2015–2016.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6); second, third terms. Prerequisite: ME 119 a or equivalent.* The course will cover thermodynamics of pure substances and mixtures, equations of state, chemical equilibrium, chemical kinetics, combustion chemistry, transport phenomena, and the governing equations for multicomponent gas mixtures. Topics will be chosen from non-premixed and premixed flames, the fluid mechanics of laminar flames, flame mechanisms of combustion-generated pollutants, and numerical simulations of multicomponent reacting flows. Not offered 2015–2016.

Ae 121 abc. Space Propulsion. *9 units (3-0-6); each term. Open to all graduate students and to seniors with instructor's permission.* Ae 121 is designed to introduce the fundamentals of chemical, electric and advanced propulsion technologies. The course focuses on the thermochemistry and aerodynamics of chemical and electrothermal propulsion systems, the physics of ionized gases and electrostatic and electromagnetic processes in electric thrusters. These analyses provide the opportunity to introduce the basic concepts of non-equilibrium gas dynamics and kinetic theory. Specific technologies such as launch vehicle rocket engines, monopropellant engines, arcjets, ion thrusters, magnetoplasmadynamic engines and Hall thrusters will be discussed. Ae 121 also provides an introduction to advanced propulsion concepts such as solar sails and antimatter rockets. Instructor: Polk.

Ae 150 abc. Aerospace Engineering Seminar. *1 unit; first, second, third terms.* Speakers from campus and outside research and manufacturing organizations discuss current problems and advances in aerospace engineering. Graded pass/fail. Instructor: McKeon.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second terms.* For course description, see Electrical Engineering.

Ae 159. Space Optical System Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 2, EE/Ae 157, or equivalent; APh 23 desirable.* Introduction to optical system engineering for remote sensing from space will be presented. End-to-end optical systems are discussed within the framework of the 10 scientific/technical disciplines required to build a successful system: optical engineering, physical optics of materials, solid-state physics/detectors, mechanics and mechanisms engineering, wavefront sensing and control, structures and dynamics, thermal engineering, spacecraft engineering, psychology of vision and software processing of images, and end-to-end system validation and calibration. Emphasis will be on the development of optical engineering tools. Instructor: Breckinridge.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6); first, second terms.* Elements of Cartesian tensors. Configurations and motions of a body. Kinematics—study of deformations, rotations and stretches, polar decomposition. Lagrangian and Eulerian strain velocity and spin tensor fields. Irrotational motions, rigid motions. Kinetics—balance laws. Linear and angular momentum, force, traction stress. Cauchy's theorem, properties of Cauchy's stress. Equations of motion, equilibrium equations. Power theorem, nominal (Piola-Kirchoff) stress. Thermodynamics of bodies. Internal energy, heat flux, heat supply. Laws of thermodynamics, notions of entropy, absolute temperature. Entropy inequality (Clausius-Duhem). Examples of special classes of constitutive laws for materials without memory. Objective rates, corotational, convected rates. Principles of materials frame indifference. Examples: the isotropic Navier-Stokes fluid, the isotropic thermoelastic solid. Basics of finite differences, finite elements, and boundary integral methods, and their applications to continuum mechanics problems illustrating a variety of classes of constitutive laws. Instructor: Kochmann.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5); first, second terms. Prerequisite: Ae/AM/CE/ME 102 a or ME 65.* Introduction and fabrication technology, elastic deformation of composites, stiffness bounds, on- and off-axis elastic constants for a lamina, elastic deformation of multidirectional laminates (lamination theory, ABD matrix), effective hygrothermal properties, mechanisms of yield and failure for a laminate, strength of a single ply, failure models, splitting and delamination. Experimental methods for characterization and testing of composite materials. Design criteria, application of design methods to select a suitable laminate using composite design software, hand layup of a simple laminate and measurement of its stiffness and thermoelastic coefficients. Pellegrino.

Ae 200. Advanced Research in Aerospace. *Units to be arranged.* Ae.E. or Ph.D. thesis level research under the direction of the staff. A written research report must be submitted during finals week each term.

Ae 201 ab. Advanced Fluid Mechanics. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM 101 (may be taken concurrently).* Foundations of the mechanics of real fluids. Basic concepts will be emphasized. Subjects covered will include a selection from the following topics: physical properties of real gases; the equations of motion of viscous and inviscid fluids; the dynamical significance of vorticity; vortex dynamics; exact solutions; motion at high Reynolds numbers; hydrodynamic stability; boundary layers; flow past bodies; compressible flow; subsonic, transonic, and supersonic flow; shock waves. Instructors: Pullin, Meiron.

Ae 204. Technical Fluid Mechanics. *9 units (3-0-6); first term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* External and internal flow problems encountered in engineering, for which only empirical methods exist. Turbulent shear flow, separation, transition, three-dimensional and nonsteady effects. Basis of engineering practice in the design of devices such as mixers, ejectors, diffusers, and control valves. Studies of flow-induced oscillations, wind effects on structures, vehicle aerodynamics. Not offered 2015–16.

Ae 205 ab. Advanced Space Project. *9 units (2-4-3); second, third terms. Prerequisites: Ae105 abc.* This is an advanced course on the design and implementation of space projects and it is currently focused on the flight project Autonomous Assembly of a Reconfigurable Space Telescope (AAReST). The objective is to be ready for launch and operation in 2015. Each student will be responsible for a specific activity, chosen from the following: optimization of telescope system architecture; design, assembly and testing of telescope optics; telescope calibration procedure and algorithms for wavefront control; thermal analysis; boom design and deployment test methods; effects of spacecraft dynamics on telescope performance; environmental testing of telescope system. Each student will prepare a survey of the state of the art for the selected activity, and then develop a design/implementation plan, execute the plan and present the results in a final report. Instructor: Pellegrino.

Ae 208 abc. GALCIT Colloquium. *1 unit; first, second, third terms.* A seminar course in fluid, solid, space, and bio mechanics. Weekly lectures on current developments are presented by staff members, graduate students, and visiting scientists and engineers. Graded pass/fail. Instructors: Kochmann, Austin.

Note: The following courses, with numbers greater than 209, are one-, two-, or three-term courses offered to interested students. Depending on conditions, some of the courses may be taught as tutorials or reading courses, while others may be conducted more formally.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE/ME 102 abc (concurrently) or equivalent and instructor's permission.* Analytical and experimental techniques in the study of fracture in metallic and nonmetallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of nontraditional materials. Fatigue crack growth and life prediction techniques will also be discussed. In addition, "dynamic" stress wave dominated, failure initiation growth and arrest phenomena will be covered. This will include traditional dynamic fracture considerations as well as discussions of failure by adiabatic shear localization. Instructor: Ortiz.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: AM 125 abc or equivalent; ACM 100 abc or equivalent; CE/AM/Ae 108 abc or equivalent or instructor's permission; Ae/AM/CE/ME 102 abc or equivalent; Ae/Ge/ME 160 ab desirable or taken concurrently.* Introduction to the use of numerical methods in the solution of solid mechanics and materials problems. First term: geometrical representation of solids. Automatic meshing. Approximation theory. Interpolation error estimation. Optimal and adaptive meshing. Second term: variational principles in linear elasticity. Finite element analysis. Error estimation. Convergence. Singularities. Adaptive strategies. Constrained problems. Mixed methods. Stability and convergence. Variational problems in nonlinear elasticity. Consistent linearization. The Newton-Rahpson method. Bifurcation analysis. Adaptive strategies in nonlinear elasticity. Constrained finite deformation problems. Contact and friction. Third term: time integration. Algorithm analysis. Accuracy, stability, and convergence. Operator splitting and product formulas. Coupled problems. Impact and friction. Subcycling. Space-time methods. Inelastic solids. Constitutive updates. Stability and convergence. Consistent linearization. Applications to finite deformation viscoplasticity, viscoelasticity, and Lagrangian modeling of fluid flows. Not offered 2015–16.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6); second term. Prerequisites: ACM 100 abc or AM 125 abc; Ae/AM/CE/ME 102 abc.* Fundamentals of theory of wave propagation; plane waves, wave guides, dispersion relations; dynamic plasticity, adiabatic shear banding; dynamic fracture; shock waves, equation of state. Not offered 2015–16.

Ae/ME 218. Statistical Mechanics. *3-0-6; second term. Prerequisites: Ae/ME118, or equivalent.* Overview of probability and statistics, and the Maxwell-Boltzmann distribution. Overview and elements of Quantum Mechanics, degenerate energy states, particles in a box, and energy-state phase space. Statistics of indistinguishable elementary particles, Fermi-Dirac and Bose-Einstein statistics, partition functions, connections with classical thermodynamics, and the Law of Equipartition. Examples from equilibrium in fluids, solid-state physics, and others. Not offered 2015–2016.

Ae 220. Theory of Structures. *9 units (3-0-6); first term. Prerequisite: Ae/AM/CE/ME 102 abc.* Fundamentals of buckling and stability, total potential energy and direct equilibrium approaches; classification of instabilities into snap-through type and bifurcation type; rigid-elastic structures, eigenvalues, and eigenvectors of stiffness matrix; elastic structures; approximate estimates of buckling load; Rayleigh quotient; lateral buckling of columns: Euler strut, imperfections, Southwell plot, beam-columns, stability coefficients, buckling of frames; elasto-plastic buckling: tangent-modulus, double-modulus, Shanley's analysis; lateral-torsional buckling of beams; buckling of plates; buckling of cylindrical shells. Not offered 2015–16.

Ae/CE 221. Space Structures. *9 units (3-0-6); first term.* This course examines the links between form, geometric shape, and structural performance. It deals with different ways of breaking up a continuum, and how this affects global structural properties; structural concepts and preliminary design methods that are used in tension structures and deployable structures. Geometric foundations, polyhedra and tessellations, surfaces; space frames, examples of space frames, stiffness and structural efficiency of frames with different repeating units; sandwich plates; cable and membrane structures, form-finding, wrinkle-free pneumatic domes, balloons, tension-stabilized struts, tensegrity domes; deployable and adaptive structures, coiled rods and their applications, flexible shells, membranes, structural mechanisms, actuators, concepts for adaptive trusses and manipulators. Not offered 2015–2016.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6); third term. Prerequisite: Ae/AM/CE/ME 102 abc or instructor's permission.* Theory of dislocations in crystalline media. Characteristics of dislocations and their influence on the mechanical behavior in various crystal structures. Application of dislocation theory to single and polycrystal plasticity. Theory of the inelastic behavior of materials with negligible time effects. Experimental background for metals and fundamental postulates for plastic stress-strain relations. Variational principles for incremental elastic-plastic problems, uniqueness. Upper and lower bound theorems of limit analysis and shakedown. Slip line theory and applications. Additional topics may include soils, creep and rate-sensitive effects in metals, the thermodynamics of plastic deformation, and experimental methods in plasticity. Instructor: Ortiz.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged; first, second, third terms.* Subject matter changes depending upon staff and student interest. (1) Stress Waves in Solids. 9 units (3-0-6); second term. Stress waves will be introduced by considering plane waves which allow the principal features of stress wave propagation to be explored without introducing the geometric complexities of waves in 3D. Formulation will include elastic materials and dissipative materials that are modeled as viscoelastic or viscoplastic. For elastic materials, we will consider waves in unbounded anisotropic media, refraction at plane boundaries, surface waves, wave guides, phase velocity and group velocity, waves in periodic media, energy transport, and diffraction. For dissipative materials, we will consider frequency- dependent attenuation, elastic precursor decay, and nonlinear waves in 1D. Examples, and opportunities to explore more advanced topics, will be chosen to try to respond to student interests. Not offered 2015–2016.

Ae 228. Computational Mechanics Simulations Using Particles. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE/ME 214 or equivalent or Ae/ACM/ME 232 or equivalent, ACM 104, ACM 105, or equivalent.* Particle simulations of continuum and discrete systems. Advances in molecular, mesoscopic, and macroscale simulations using particles, identification of common computing paradigms and challenges across disciplines, discretizations and representations using particles, fast summation algorithms, time integrators, constraints, and multiresolution. Exercises will draw on problems simulated using particles from diverse areas such as fluid and solid mechanics, computer graphics, and nanotechnology. Not offered 2015–16.

Ae/ACM/ME 232 ab. Computational Fluid Dynamics. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; ACM 100 abc or equivalent.* Development and analysis of algorithms used in the solution of fluid mechanics problems. Numerical analysis of discretization schemes for partial differential equations including interpolation, integration, spatial discretization, systems of ordinary differential equations; stability, accuracy, aliasing, Gibbs and Runge phenomena, numerical dissipation and dispersion; boundary conditions. Survey of finite difference, finite element, finite volume and spectral approximations for the numerical solution of the incompressible and compressible Euler and Navier-Stokes equations, including shock-capturing methods. Not offered 2015–2016.

Ae 233. Hydrodynamic Stability. *9 units (3-0-6); third term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* Laminar-stability theory as a guide to laminar-turbulent transition. Rayleigh equation, instability criteria, and response to small inviscid disturbances. Discussion of Kelvin-Helmholtz, Rayleigh-Taylor, Richtmyer-Meshkov, and other instabilities, for example, in geophysical flows. The Orr-Sommerfeld equation, the dual role of viscosity, and boundary-layer stability. Modern concepts such as pseudomomentum conservation laws and nonlinear stability theorems for 2-D and geophysical flows. Weakly nonlinear stability theory and phenomenological theories of turbulence. Not offered 2015–2016.

Ae 234. Hypersonic Aerodynamics. *9 units (3-0-6); first term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent, AM 125 abc, or instructor's permission.* An advanced course dealing with aerodynamic problems of flight at hypersonic speeds. Topics are selected from hypersonic small-disturbance theory, blunt-body theory, boundary layers and shock waves in real gases, heat and mass transfer, testing facilities and experiment. Not offered 2015–16.

Ae 235. Rarefied Gasdynamics. *9 units (3-0-6); third term.* Molecular description of matter; distribution functions; discrete-velocity gases. Kinetic theory: free-path theory, internal degrees of freedom. Boltzmann equation: BBGKY hierarchy and closure, H theorem, Euler equations, Chapman-Enskog procedure, free-molecule flows. Collisionless and transitional flows. Direct simulation Monte Carlo methods. Applications. Not offered 2015–16.

Ae 237 a. Nonsteady Gasdynamics. *9 units (3-0-6); second term.* Part a: dynamics of shock waves, expansion waves, and related discontinuities in gases. Adiabatic phase-transformation waves. Interaction of waves in one- and two-dimensional flows. Boundary layers and shock structure. Applications and shock tube techniques. Part b: shock and detonation waves in solids and liquids. Equations of state for hydrodynamic computations in solids, liquids, and explosive reaction products. CJ and ZND models of detonation in solids and liquids. Propagation of shock waves and initiation of reaction in explosives. Interactions of detonation waves with water and metals. Not offered 2015–16.

Ae 239 ab. Turbulence. *9 units (3-0-6); second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM 101.* Reynolds-averaged equations and the problem of closure. Statistical description of turbulence. Homogeneous isotropic turbulence and structure of fine scales. Turbulent shear flows. Physical and spectral models. Subgridscale modeling. Turbulent mixing. Structure of low and high Reynolds number wall turbulence. Instructor: Dimotakis.

Ae 240. Special Topics in Fluid Mechanics. *Units to be arranged; first, second, third terms.* Subject matter changes depending upon staff and student interest. (1) Educational exchange at Ecole Polytechnique. Students participating in the Ecole Polytechnique educational exchange must register for 36 units while they are on detached duty at Ecole Polytechnique. For further information refer to the graduate option information for Aerospace. Instructor: McKeon.

Ae 241. Special Topics in Experimental Fluid and Solid Mechanics. *Prerequisite: Ae/APh 104 or equivalent or instructor's permission. Units to be arranged; first, second, third terms.* Subject matter changes depending upon staff and student interest.

Ae/BE 242. Biological Flows: Propulsion. *9 units (3-0-6); third term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Physical principles of unsteady fluid momentum transport: equations of motion, dimensional analysis, conservation laws. Unsteady vortex dynamics: vorticity generation and dynamics, vortex dipoles/rings, wake structure in unsteady flows. Life in moving fluids: unsteady drag, added-mass effects, virtual buoyancy, bounding and schooling, wake capture. Thrust generation by flapping, undulating, rowing, jetting. Low Reynolds number propulsion. Bioinspired design of propulsion devices. Not offered 2015–2016.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6); second term.* For course description, see Medical Engineering.

Ae 244. Mechanics of Nanomaterials. *9 units (3-0-6); second term.* Basics of the mechanics of nanomaterials, including the physical and chemical synthesis/processing techniques for creating nanostructures and their relation with mechanical and other structural properties.Overview of the properties of various types of nanomaterials including nanostructured metals/ceramics/composites, nanowires, carbon nanotubes, quantum dots, nanopatterns, self-assembled colloidal crystals, magnetic nanomaterials, and biorelated nanomaterials. Innovative experimental methods and microstructural characterization developed for studying the mechanics at the nanoscale will be described. Recent advances in the application of nanomaterials in engineering systems and patent-related aspects of nanomaterials will also be covered. Open to undergraduates with instructor's permission. Not offered 2015–16.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. *9 units; (3-0-6 a, 1-6-1- b); second, third term. Prerequisites: ACM 100abc, Ae/APh/CE/ME 101abc or equivalent.* This course seeks to introduce students to recent developments in theoretical and practical aspects of applying control to flow phenomena and fluid systems. Lecture topics in the second term drawn from: the objectives of flow control; a review of relevant concepts from classical and modern control theory; high-fidelity and reduced-order modeling; principles and design of actuators and sensors. Third term: laboratory work in open- and closed-loop control of boundary layers, turbulence, aerodynamic forces, bluff body drag, combustion oscillations and flow-acoustic oscillations. Not offered 2015–16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6)*. For course description, see Mechanical Engineering.

ANTHROPOLOGY

An 22. Introduction to Sociocultural Anthropology. *9 units (3-0-6); third term.* Introduction to anthropological theory. Exploration of the diversity of human culture. Examination of the relationship between ecology, technology, and subsistence, patterns of marriage and residence, gender and sexual division of labor, reproduction, kinship, and descent. Links between economic complexity, population, social stratification, political organization, law, religion, ritual, and warfare are traced. Ethnic diversity and interethnic relations are surveyed. The course is oriented toward understanding the causes of cross-cultural variation and the evolution of culture. Instructor: Ensminger.

An 23. Human Evolution. *9 units (3-0-6); first term.* Introduction to human evolution, which is essential for understanding our species. Natural selection, sexual selection, genetics, systematics, behavioral ecology, and life history theory are covered. The order Primates is surveyed. Primary emphasis is on the hominid fossil and archeological record. Behavior, cognition, and culture of nonhuman primates and humans, as well as physical variation in present-day humans, is examined. Instructor: Abrams.

An 97. Undergraduate Research. *Units to be arranged; any term. Prerequisites: advanced Anthropology and instructor's permission..* This course offers advanced undergraduates the opportunity to pursue research in Anthropology individually or in a small group. Graded pass/fail.

An 101. Selected Topics in Anthropology. *Units to be determined by arrangement with the instructor; offered by announcement.* Topics to be determined by instructor. Instructor: Staff.

H/An 123. Anthropological Demography. *9 units (3-0-6); first term.* For course description, see History.

An/PS 127. Corruption. *9 units (3-0-6); third term. Prerequisites: AN 22 or PS 12.* Corruption taxes economies and individuals in both the developing and the developed world. We will examine what corruption means in different places and contexts, from grand financial scandals to misappropriation of development funds, ethnic patronage, and the theft of elections. How do we measure it? What are its costs and social consequences? What are its correlates? Does freedom of information matter? Students will read across a range of topics, and write an in-depth research paper on one topic. Limited enrollment. Instructor: Ensminger.

An 135. Primate Behavior. *9 units (3-0-6); third term.* This course will examine how natural selection has shaped the social organization, life histories, reproductive strategies, social behavior, and cognitive abilities of nonhuman primates. It will review natural and sexual selection, examine the ecological and social pressures that shape primate behavior, and consider the role these principles play in shaping modern human behavior. Instructor: Staff. Not offered 2015–16.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Students in this class will help develop hypotheses, methods, and background information for the design of a new class to be offered in subsequent years, which will seek to pose and empirically test questions related to cultural and social aspects of the Caltech undergraduate experience. Central to this project will be an examination of the theory of social networks and the role they play in the academic and social experience. Other qualitative and quantitative methods for future data gathering will also be designed. Not offered 2015–16.

An 150. The Caltech Project. *9 units (3-0-6), spring term. Prerequisites: An 22 or permission of instructor.* Hands-on immersion in a social scientific research project examining the Caltech undergraduate community. Core data collection includes a social network analysis and a rich array of socio-demographic data from the actual Caltech student body. Students will develop research design skills by writing and revising a 3000 word research proposal modeled on the NSF format. This unique data set allows us to address questions as diverse as: the impact of social networks upon academic performance, the origin and extent of socio-cultural differences across houses, and the diffusion of moral, political, academic, and religious values. Not offered 2015–16.

APPLIED AND COMPUTATIONAL MATHEMATICS

ACM 11. Introduction to Matlab and Mathematica. *6 units (2-2-2); third term. Prerequisites: Ma 1 abc. CS 1 or prior programming experience recommended.* Matlab: basic syntax and development environment; debugging; help interface; basic linear algebra; visualization and graphical output; control flow; vectorization; scripts, and functions; file i/o; arrays, structures, and strings; numerical analysis (topics may include curve fitting, interpolation, differentiation, integration, optimization, solving nonlinear equations, fast Fourier transform, and ODE solvers); and advanced topics (may include writing fast code, parallelization, object-oriented features). Mathematica: basic syntax and the notebook interface, calculus and linear algebra operations, numerical and symbolic solution of algebraic and differential equations, manipulation of lists and expressions, Mathematica programming (rule-based, functional, and procedural) and debugging, plotting, and visualization. The course will also emphasize good programming habits and choosing the appropriate language/software for a given scientific task. Instructors: Staff.

ACM 95/100 ab. Introductory Methods of Applied Mathematics for the Physical Sciences. *12 units (4-0-8); second, third terms. Prerequisites: Ma 1 abc, Ma 2 or equivalents.* Complex analysis: analyticity, Laurent series, contour integration, residue calculus. Ordinary differential equations: linear initial value problems, linear boundary value problems, Sturm-Liouville theory, eigenfunction expansions, transform methods, Green's functions. Linear partial differential equations: heat equation, separation of variables, Laplace equation, transform methods, wave equation, method of characteristics, Green's functions. Instructors: Meiron, Pierce.

ACM 101 ab. Methods of Applied Mathematics. *12 units (4-0-8); first, second, terms. Prerequisites: Math 2/102 and ACM 95ab.* First term: brief review of the elements of complex analysis and complex-variable methods. Asymptotic expansions, asymptotic evaluation of integrals (Laplace method, stationary phase, steepest descents), perturbation methods, WKB theory, boundary-layer theory, matched asymptotic expansions with first-order and high-order matching. Method of multiple scales for oscillatory systems. Second term: applied spectral theory, special functions, Hilbert spaces and linear operators, generalized eigenfunction expansions, convergence theory. Transform methods, distributions, Fourier Transform and Sobolev Spaces. Eigensystems and spectral theory for self-adjoint second order operators with variable coefficients in n-dimensional domains. Integral equations, Fredholm theorem, application to Laplace and Maxwell's equations, harmonicity at infinity, Kelvin transform, conditions of radiation at infinity. Instructor: Bruno.

CMS/ACM 104. Linear Algebra and Applied Operator Theory. *12 units (3-0-9); first term.* For course description, see Computation and Mathematical Sciences.

ACM 105. Applied Real and Functional Analysis. *9 units (3-0-6); second term. Prerequisite: ACM 100 ab or instructor's permission.* Lebesgue integral on the line, general measure and integration theory; Lebesgue integral in n-dimensions, convergence theorems, Fubini, Tonelli, and the transformation theorem; normed vector spaces, completeness, Banach spaces, Hilbert spaces; dual spaces, Hahn-Banach theorem, Riesz-Frechet theorem, weak convergence and weak solvability theory of boundary value problems; linear operators, existence of the adjoint. Self-adjoint operators, polar decomposition, positive operators, unitary operators; dense subspaces and approximation, the Baire, Banach-Steinhaus, open mapping and closed graph theorems with applications to differential and integral equations; spectral theory of compact operators; LP spaces, convolution; Fourier transform, Fourier series; Sobolev spaces with application to PDEs, the convolution theorem, Friedrich's mollifiers. Instructor: Tropp.

ACM 106 ab. Introductory Methods of Computational Mathematics. *12 units (3-0-9); second, third terms. Prerequisites: Ma 1 abc, Ma 2, Ma 3, ACM 11, ACM 95/100 ab or equivalent.* The sequence covers the introductory methods in both theory and implementation of numerical linear algebra, approximation theory, ordinary differential equations, and partial differential equations. The linear algebra parts covers basic methods such as direct and iterative solution of large linear systems, including LU decomposition, splitting method (Jacobi iteration, Gauss-Seidel iteration); eigenvalue and vector computations including the power method, QR iteration and Lanczos iteration; nonlinear algebraic solvers. The approximation theory includes data fitting; interpolation using Fourier transform, orthogonal polynomials and splines; least square method, and numerical quadrature. The ODE parts include initial and boundary value problems. The PDE parts include finite difference and finite element for elliptic/parabolic/hyperbolic equation. Stability analysis will be covered with numerical PDE. Programming is a significant part of the course. Instructor: Hou.

CMS/ACM 113. Mathematical Optimization. *9 units (3-0-6); first term.* See course description in Computation and Mathematical Sciences.

ACM/CS 114 ab. Parallel Algorithms for Scientific Applications. *9 units (3-0-6); second, third term. Prerequisites: ACM 11, 106 or equivalent.* Introduction to parallel program design for numerically intensive scientific applications. Parallel programming methods; distributed-memory model with message passing using the message passing interface; shared-memory model with threads using open MP, CUDA; object-based models using a problem-solving environment with parallel objects. Parallel numerical algorithms: numerical methods for linear algebraic systems, such as LU decomposition, QR method, CG solvers; parallel implementations of numerical methods for PDEs, including finite-difference, finite-element; particle-based simulations. Performance measurement, scaling and parallel efficiency, load balancing strategies. Not offered 2015–16.

CMS/ACM 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6); first term.* For course description, see Computation and Mathematical Sciences.

AM/ACM 127. Calculus of Variations. *9 units (3-0-6)* For course description, see Applied Mechanics.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6).* For course description, see Mathematics.

Ma/ACM 144 ab. Probability. *9 units (3-0-6); second, third terms.* For course description, see Mathematics.

ACM/EE 170. Mathematics of Signal Processing. *12 units (3-0-9); third term. Prerequisites: CMS/ACM 104, CMS/ACM 113, and CMS/ACM 116; or instructor's permission.* This course covers classical and modern approaches to problems in signal processing. Problems may include denoising, deconvolution, spectral estimation, direction-of-arrival estimation, array processing, independent component analysis, system identification, filter design, and transform coding. Methods rely heavily on linear algebra, convex optimization, and stochastic modeling. In particular, the class will cover techniques based on least-squares and on sparse modeling. Throughout the course, a computational viewpoint will be emphasized. Not offered 2015–16.

ACM 190. Reading and Independent Study. *Units by arrangement.* Graded pass/fail only.

ACM 201 ab. Partial Differential Equations. *12 units (4-0-8); first, second terms. Prerequisite: ACM 11, 101 abc or instructor's permission.* Fully nonlinear first-order PDEs, shocks, eikonal equations. Classification of second-order linear equations: elliptic, parabolic, hyperbolic. Well-posed problems. Laplace and Poisson equations; Gauss's theorem, Green's function. Existence and uniqueness theorems (Sobolev spaces methods, Perron's method). Applications to irrotational flow, elasticity, electrostatics, etc. Heat equation, existence and uniqueness theorems, Green's function, special solutions. Wave equation and vibrations. Huygens' principle. Spherical means. Retarded potentials. Water waves and various approximations, dispersion relations. Symmetric hyperbolic systems and waves. Maxwell equations, Helmholtz equation, Schrödinger equation. Radiation conditions. Gas dynamics. Riemann invariants. Shocks, Riemann problem. Local existence theory for general symmetric hyperbolic systems. Global existence and uniqueness for the inviscid Burgers' equation. Integral equations, single- and double-layer potentials. Fredholm theory. Navier-Stokes equations. Stokes flow, Reynolds number. Potential flow; connection with complex variables. Blasius formulae. Boundary layers. Subsonic, supersonic, and transonic flow. Not offered 2015–16.

ACM 204. Topics in Convexity. *9 units (3-0-6); second term. Prerequisites: CMS/ACM 104 and CMS/ACM 113; or instructor's permission.* The content of this course varies from year to year among advanced subjects in linear algebra, convex analysis, and related fields. Specific topics for the class include matrix analysis, operator theory, convex geometry, or convex algebraic geometry. Lectures and homework will require the ability to understand and produce mathematical proofs. Not overed 2015–16.

ACM 210 ab. Numerical Methods for PDEs. *9 units (3-0-6); second, third terms. Prerequisite: ACM 11, 106 or instructor's permission.* Finite difference and finite volume methods for hyperbolic problems. Stability and error analysis of nonoscillatory numerical schemes: i) linear convection: Lax equivalence theorem, consistency, stability, convergence, truncation error, CFL condition, Fourier stability analysis, von Neumann condition, maximum principle, amplitude and phase errors, group velocity, modified equation analysis, Fourier and eigenvalue stability of systems, spectra and pseudospectra of nonnormal matrices, Kreiss matrix theorem, boundary condition analysis, group velocity and GKS normal mode analysis; ii) conservation laws: weak solutions, entropy conditions, Riemann problems, shocks, contacts, rarefactions, discrete conservation, Lax-Wendroff theorem, Godunov's method, Roe's linearization, TVD schemes, high-resolution schemes, flux and slope limiters, systems and multiple dimensions, characteristic boundary conditions; iii) adjoint equations: sensitivity analysis, boundary conditions, optimal shape design, error analysis. Interface problems, level set methods for multiphase flows, boundary integral methods, fast summation algorithms, stability issues. Spectral methods: Fourier spectral methods on infinite and periodic domains. Chebyshev spectral methods on finite domains. Spectral element methods and h-p refinement. Multiscale finite element methods for elliptic problems with multiscale coefficients. Not offered 2015–16.

ACM 213. Topics in Optimization. *9 units (3-0-6); third term. Prerequisites: CMS/ACM 104, CMS/ACM 113.* Material varies year-to-year. Example topics include discrete optimization, convex and computational algebraic geometry, numerical methods for large-scale optimization, and convex geometry. Instructors: Chandrasekaran.

ACM 216. Markov Chains, Discrete Stochastic Processes and Applications. *9 units (3-0-6); second term. Prerequisite: ACM/EE 116 or equivalent.* Stable laws, Markov chains, classification of states, ergodicity, von Neumann ergodic theorem, mixing rate, stationary/equilibrium distributions and convergence of Markov chains, Markov chain Monte Carlo and its applications to scientific computing, Metropolis Hastings algorithm, coupling from the past, martingale theory and discrete time martingales, rare events, law of large deviations, Chernoff bounds. Instructor: Owhadi.

ACM 217 ab. Advanced Topics in Stochastic Analysis. *9 units (3-0-6); third term. Prerequisite: ACM 216 or equivalent.* The topic of this course changes from year to year and is expected to cover areas such as stochastic differential equations, stochastic control, statistical estimation and adaptive filtering, empirical processes and large deviation techniques, concentration inequalities and their applications. Examples of selected topics for stochastic differential equations include continuous time Brownian motion, Ito's calculus, Girsanov theorem, stopping times, and applications of these ideas to mathematical finance and stochastic control. Not offered 2015–16.

ACM/CS/EE 218. Statistical Inference. *9 units (3-0-6); third term. Prerequisites: CMS/ACM 104 and CMS/ACM/EE 116, or instructor's permission.*

Fundamentals of estimation theory and hypothesis testing; Bayesian and non-Bayesian approaches; minimax analysis, Cramer-Rao bounds, shrinkage in high dimensions; Kalman filtering, basics of graphical models; statistical model selection. Throughout the course, a computational viewpoint will be emphasized. Not offered 2015–16.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ACM 256 ab. Special Topics in Applied Mathematics. *9 units (3-0-6); first term. Prerequisite: ACM 101 or equivalent.* Introduction to finite element methods. Development of the most commonly used method—continuous, piecewise-linear finite elements on triangles for scalar elliptic partial differential equations; practical (a posteriori) error estimation techniques and adaptive improvement; formulation of finite element methods, with a few concrete examples of important equations that are not adequately treated by continuous, piecewise-linear finite elements, together with choices of finite elements that are appropriate for those problems. Homogenization and optimal design. Topics covered include periodic homogenization, G- and H-convergence, Gamma-convergence, G-closure problems, bounds on effective properties, and optimal composites. Not offered 2015–16.

ACM 257. Special Topics in Financial Mathematics. *9 units (3-0-6); third term. Prerequisite: ACM 95/100 or instructor's permission. A basic knowledge of probability and statistics as well as transform methods for solving PDEs is assumed.* This course develops some of the techniques of stochastic calculus and applies them to the theory of financial asset modeling. The mathematical concepts/tools developed will include introductions to random walks, Brownian motion, quadratic variation, and Ito-calculus. Connections to PDEs will be made by Feynman-Kac theorems. Concepts of risk-neutral pricing and martingale representation are introduced in the pricing of options. Topics covered will be selected from standard options, exotic options, American derivative securities, term-structure models, and jump processes. Not offered 2015–16.

ACM 270. Advanced Topics in Applied and Computational Mathematics. *Hours and units by arrangement; second, third terms.* Advanced topics in applied and computational mathematics that will vary according to student and instructor interest. May be repeated for credit. Instructor: Staff.

ACM 300. Research in Applied and Computational Mathematics. *Units by arrangement.*

APPLIED MECHANICS

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aerospace.

CE/Ae/AM 108 ab. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

AM/ACM 127. Calculus of Variations. *9 units (3-0-6); third term. Prerequisites: ACM 95/100.* First and second variations; Euler-Lagrange equation; Hamiltonian formalism; action principle; Hamilton-Jacobi theory; stability; local and global minima; direct methods and relaxation; isoperimetric inequality; asymptotic methods and gamma convergence; selected applications to mechanics, materials science, control theory and numerical methods. Not offered 2015–16.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term; first, second and third terms.* Students attend a graduate seminar each week of each term and submit a report about the attended seminars. At least four of the attended seminars each term should be from the Mechanical and Civil Engineering seminar series. Students not registered for the M.S. and Ph.D. degrees must receive the instructor's permission. Graded pass/fail. Instructor: Staff.

AM/CE 151 ab. Dynamics and Vibration. *9 units (3-0-6); first, second terms.* Equilibrium concepts, conservative and dissipative systems, Lagrange's equations, differential equations of motion for discrete single and multi degree-of-freedom systems, natural frequencies and mode shapes of these systems (Eigen value problem associated with the governing equations), phase plane analysis of vibrating systems, forms of damping and energy dissipated in damped systems, response to simple force pulses, harmonic and earthquake excitation, response spectrum concepts, vibration isolation, seismic instruments, dynamics of continuous systems, Hamilton's principle, axial vibration of rods and membranes, transverse vibration of strings, beams (Bernoulli-Euler and Timoshenko beam theory), and plates, traveling and standing wave solutions to motion of continuous systems, Rayleigh quotient and the Rayleigh-Ritz method to approximate natural frequencies and mode shapes of discrete and continuous systems, frequency domain solutions to dynamical systems, stability criteria for dynamical systems, and introduction to nonlinear systems and random vibration theory. Instructors: Heaton, Asimaki.

AM/ME 165 ab. Elasticity. *9 units (3-0-6); second, third terms. Prerequisites: Ae/Ge/ME 160 a and registered in Ae/Ge/ME 160 b.* Fundamental concepts and equations of elasticity. Linearized theory of elastostatics and elastodynamics: basic theorems and special solutions. Finite theory of elasticity: constitutive theory, semi-inverse methods. Variational methods. Applications to problems of current interest. Not offered 2015–16.

AM 200. Advanced Work in Applied Mechanics. *Hours and units by arrangement.* A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

AM 201. Advanced Topics in Applied Mechanics. *9 units (3-0-6).* The faculty will prepare courses on advanced topics to meet the needs of graduate students.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

AM 300. Research in Applied Mechanics. *Hours and units by arrangement. Research in the field of applied mechanics.* By arrangement with members of the staff, properly qualified graduate students are directed in research.

APPLIED PHYSICS

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5).* For course description, see Chemistry.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2); first, third terms; six units credit for the freshman laboratory requirement. Prerequisite: Successful completion of APh/EE 9 a is a prerequisite for enrollment in APh/EE 9 b.* Introduction to solid-state electronics, including physical modeling and device fabrication. Topics: semiconductor crystal growth and device fabrication technology, carrier modeling, doping, generation and recombination, pn junction diodes, MOS capacitor and MOS transistor operation, and deviations from ideal behavior. Laboratory includes computer-aided layout, and fabrication and testing of light-emitting diodes, transistors, and inverters. Students learn photolithography, and use of vacuum systems, furnaces, and device-testing equipment. Instructor: Scherer.

APh 17 abc. Thermodynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Introduction to the use of thermodynamics and statistical mechanics in physics and engineering. Entropy, temperature, and the principal laws of thermodynamics. Canonical equations of state. Applications to cycles, engines, phase and chemical equilibria. Probability and stochastic processes. Kinetic theory of perfect gases. Statistical mechanics. Applications to gases, gas degeneration, equilibrium radiation, and simple solids. Not offered 2015–2016. APh majors are required to take Ph 12 instead.

APh 23. Demonstration Lectures in Optics. *6 units (2-0-4); second term. Prerequisites: Ph 1 abc.* This course cover fundamentals of optics with emphasis on modern optical applications, intended to exhibit basic optical phenomena including interference, dispersion, birefringence, diffraction, and laser oscillation, and the applications of these phenomena in optical systems employing two-beam and multiple-beam interferometry, Fourier-transform image processing, holography, electro-optic modulation, and optical detection and heterodyning. System examples to be selected from optical communications, radar, adaptive optical systems and nano-photonic devices. Instructor: Faraon.

APh 24. Introductory Modern Optics Laboratory. *6 units (0-4-2); third term. Prerequisite: APh 23.* Laboratory experiments to acquaint students with the contemporary aspects of modern optical research and technology. Experiments encompass many of the topics and concepts covered in APh 23. Instructor: Faraon.

APh 77 bc. Laboratory in Applied Physics. *9 units (0-9-0); second, third terms.* Selected experiments chosen to familiarize students with laboratory equipment, procedures, and characteristic phenomena in plasmas, fluid turbulence, fiber optics, X-ray diffraction, microwaves, high-temperature superconductivity, black-body radiation, holography, and computer interfacing of experiments. Instructor: Bellan.

APh 78 abc. Senior Thesis, Experimental. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research, open only to senior-class applied physics majors. Requirements will be set by individual faculty member, but must include a written report. The selection of topic must be approved by the Applied Physics Option Representative. Not offered on a pass/fail basis. Final grade based on written thesis and oral exam. Instructor: Staff.

APh 79 abc. Senior Thesis, Theoretical. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research, open only to senior-class applied physics majors. Requirements will be set by individual faculty member, but must include a written report. The selection of topic must be approved by the Applied Physics Option Representative. Not offered on a pass/fail basis. Final grade based on written thesis and oral examThis course cannot be used to satisfy the laboratory requirement in APh. Instructor: Staff.

APh 100. Advanced Work in Applied Physics. *Units in accordance with work accomplished.* Special problems relating to applied physics, arranged to meet the needs of students wishing to do advanced work. Primarily for undergraduates. Students should consult with their advisers before registering. Graded pass/fail.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).*
For course description, see Aerospace.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6 first term; 1-3-5 second, third terms).* For course description, see Aerospace.

APh/MS 105 abc. States of Matter. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 abc or equivalent.* Thermodynamics and statistical mechanics, with emphasis on gases, liquids, materials, and condensed matter. Effects of heat, pressure, and fields on states of matter are presented with both classical thermodynamics and with statistical mechanics. Conditions of equilibrium in systems with multiple degrees of freedom. Applications include ordered states of matter and phase transitions. The three terms cover, approximately, thermodynamics, statistical mechanics, and phase transitions. Instructors: Johnson, Fultz.

APh 109. Introduction to the Micro/Nanofabrication Lab. *9 units (0-6-3); first, second, third terms.* Introduction to techniques of micro-and nanofabrication, including solid-state, optical, and microfluidic devices. Students will be trained to use fabrication and characterization equipment available in the applied physics micro- and nanofabrication lab. Topics include Schottky diodes, MOS capacitors, light-emitting diodes, microlenses, microfluidic valves and pumps, atomic force microscopy, scanning electron microscopy, and electron-beam writing. Instructor: Painter, Ghaffari.

APh 110. Topics in Applied Physics. *2 units (2-0-0); first, second terms.* A seminar course designed to acquaint advanced undergraduates and first-year graduate students with the various research areas represented in the option. Lecture each week given by a different member of the APh faculty, who will review his or her field of research. Graded pass/fail. Instructors: Painter, Bellan.

APh 114 abc. Solid-State Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 abc or equivalent.* Introductory lecture and problem course dealing with experimental and theoretical problems in solid-state physics. Topics include crystal structure, symmetries in solids, lattice vibrations, electronic states in solids, transport phenomena, semiconductors, superconductivity, magnetism, ferroelectricity, defects, and optical phenomena in solids. Instructors: Atwater, Schwab.

APh/Ph 115. Physics of Momentum Transport in Hydrodynamic Systems. *12 units (3-0-9); second term. Prerequisites: ACM 95 or equivalent.* Contemporary research in many areas of physics requires some knowledge of the principles governing hydrodynamic phenomena such as nonlinear wave propagation, symmetry breaking in pattern forming systems, phase transitions in fluids, Langevin dynamics, micro- and optofluidic control, and biological transport at low Reynolds number. This course offers students of pure and applied physics a self-contained treatment of the fundamentals of momentum transport in hydrodynamic systems. Mathematical techniques will include formalized dimensional analysis and rescaling, asymptotic analysis to identify dominant force balances, similitude, self-similarity and perturbation analysis for examining unidirectional and Stokes flow, pulsatile flows, capillary phenomena, spreading films, oscillatory flows, and linearly unstable flows leading to pattern formation. Students must have working knowledge of vector calculus, ODEs, PDEs, complex variables and basic tensor analysis. Advanced solution methods will be taught in class as needed. Second term is APh/Ph/Ae 116. Instructor: Troian.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. *12 units (3-0-9); first term. Prerequisites: ACM 95 or equivalent and APh/Ph 115 or equivalent.* Contemporary research in many areas of physics requires some knowledge of how momentum transport in fluids couples to diffusive phenomena driven by thermal or concentration gradients. This course will first examine processes driven purely by diffusion and progress toward description of systems governed by steady and unsteady convection-diffusion and reaction-diffusion. Topics will include Fickian dynamics, thermal transfer in Peltier devices, Lifshitz-Slyozov growth during phase separation, thermocouple measurements of oscillatory fields, reaction-diffusion phenomena in biophysical systems, buoyancy driven flows, and boundary layer formation. Students must have working knowledge of vector calculus, ODEs, PDEs, complex variables and basic tensor analysis. Advanced solution methods such as singular perturbation, Sturm-Liouville and Green's function analysis will be taught in class as needed. First term is APh/Ph 115. Instructor: Troian.

Ph/APh/EE/BE 118 ab. Physics of Measurement. *9 units (3-0-6); first and second terms.* For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. *9 units (3-0-6); third terms.* For course description, see Physics.

MS 132. Diffraction and Structure. *9 units (3-0-6).* For course description, see Materials Science.

MS/APh 122. Diffraction, Imaging, and Structure. *9 units (0-4-5); second and third terms.* For course description, see Materials Science.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6); first term.* Electromagnetic fields in vacuum: microscopic Maxwell's equations. Monochromatic fields: Rayleigh diffraction formulae, Huyghens principle, Rayleigh-Sommerfeld formula. The Fresnel-Fraunhofer approximation. Electromagnetic field in the presence of matter, spatial averages, macroscopic Maxwell equations. Helmholtz's equation. Group-velocity and group-velocity dispersion. Confined propagation, optical resonators, optical waveguides. Single mode and multimode waveguides. Nonlinear optics. Nonlinear propagation. Second harmonic generation. Parametric amplification. Instructor: Crosignani.

EE/APh 131. Light Interaction with Atomic Systems - Lasers. *9 units (3-0-6); second term. Prerequisites: APh/EE 130.* For course description, see Electrical Engineering.

APh/EE 132. Special Topics in Photonics and Optoelectronics. *9 units (3-0-6); third term.* Interaction of light and matter, spontaneous and stimulated emission, laser rate equations, mode-locking, Q-switching, semiconductor lasers. Optical detectors and amplifiers; noise characterization of optoelectronic devices. Propagation of light in crystals, electro-optic effects and their use in modulation of light; introduction to nonlinear optics. Optical properties of nanostructures. Not offered 2015–2016.

APh 150. Topics in Applied Physics. *Units to be arranged; first term.* Content will vary from year to year, but at a level suitable for advanced undergraduate or beginning graduate students. Topics are chosen according to the interests of students and staff. Visiting faculty may present portions of this course. Instructor: Painter.

APh 156 abc. Plasma Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106 abc or equivalent.* An introduction to the principles of plasma physics. A multitiered theoretical infrastructure will be developed consisting of the Hamilton-Lagrangian theory of charged particle motion in combined electric and magnetic fields, the Vlasov kinetic theory of plasma as a gas of interacting charged particles, the two-fluid model of plasma as interacting electron and ion fluids, and the magnetohydrodynamic model of plasma as an electrically conducting fluid subject to combined magnetic and hydrodynamic forces. This infrastructure will be used to examine waves, transport processes, equilibrium, stability, and topological self-organization. Examples relevant to plasmas in both laboratory (fusion, industrial) and space (magneto-sphere, solar) will be discussed. Instructor: Bellan.

BE/APh 161. Physical Biology of the Cell. *12 units (3-0-9).* For course description, see Bioengineering.

EE/APh 180. Nanotechnology. *6 units (3-0-3).* For course description, see Electrical Engineering.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6); third term.* Principles of semiconductor electronic structure, carrier transport properties, and optoelectronic properties relevant to semiconductor device physics. Fundamental performance aspects of basic and advanced semiconductor electronic and optoelectronic devices. Topics include energy band theory, carrier generation and recombination mechanisms, quasi-Fermi levels, carrier drift and diffusion transport, quantum transport. Instructor: Atwater.

APh 190 abc. Quantum Electronics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent.* Generation, manipulations, propagation, and applications of coherent radiation. The basic theory of the interaction of electromagnetic radiation with resonant atomic transitions. Laser oscillation, important laser media, Gaussian beam modes, the electro-optic effect, nonlinear-optics theory, second harmonic generation, parametric oscillation, stimulated Brillouin and Raman scattering. Other topics include light modulation, diffraction of light by sound, integrated optics, phase conjugate optics, and quantum noise theory. Instructor: Vahala, Painter.

APh 200. Applied Physics Research. *Units in accordance with work accomplished.* Offered to graduate students in applied physics for research or reading. Students should consult their advisers before registering. Graded pass/fail.

Ph/APh 223 ab. Advanced Condensed-Matter Physics. *9 units (3-0-6); second, third terms.* For course description, see Physics.

APh 250. Advanced Topics in Applied Physics. *Units and term to be arranged.* Content will vary from year to year; topics are chosen according to interests of students and staff. Visiting faculty may present portions of this course. Instructor: Staff.

APh 300. Thesis Research in Applied Physics. *Units in accordance with work accomplished.* APh 300 is elected in place of APh 200 when the student has progressed to the point where his or her research leads directly toward a thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

ART HISTORY

Art 11. Selected Topics in Art History. *9 units (3-0-6); offered by announcement.* Instructor: Staff.

Art 23. Major Figures in Art. *9 units (3-0-6); first term.* A course devoted to the study of a single artist of world importance, the name of the artist to be announced prior to registration. This study, grounded in the artist's life and, where possible, his/her writings, will analyze and interpret his/her major works in chronological sequence in their artistic and historic contexts, and attempt, by close aesthetic examination, to account for their greatness—and, sometimes, their failure. Not offered 2015–16.

Art 46. The Age of the Great Cathedrals. *9 units (3-0-6); third term.* A study of the arts of Western Europe from the disintegration of the Roman Empire circa A.D. 476, to the 14th century. The diverse historical forces at work during this long period produced a correspondingly varied art. Emphasis will be on the later Middle Ages, circa 1200–1350, a period marked by a synthesizing of inherited traditions into a comprehensive whole. Major monuments of architecture, such as the cathedrals of Notre Dame, Chartres, Reims, Cologne, Strasbourg, and Westminster, as well as sculpture, illuminated manuscripts, mosaics, panel painting, and stained glass will be examined within the aesthetic and social framework of countries as culturally diverse as France, Italy, Germany, Spain, and Britain. Not offered 2015–16.

Art 49. From Van Eyck to Rembrandt: Northern European Art, 1400–1650. *9 units (3-0-6); third term.* A survey of artistic developments in Northern Europe and Spain from the late Middle Ages through the Renaissance and baroque periods. The course will focus upon the complexity of northern art, from its origins in the still forceful medieval culture of 15th-century Flanders, to its confrontation with Italian Renaissance humanism in the 16th century. The effects of this cultural synthesis and the eventual development of distinct national schools of painting in the 17th century are examined through the works of the period's dominant artists, including Van Eyck, Dürer, Holbein, Velázquez, Rubens, Hals, and Rembrandt. Not offered 2015–16.

Art 50. Baroque Art. *9 units (3-0-6); first term.* A survey of the arts of painting, sculpture, and architecture from the late 16th century to the late 18th century. A confident and optimistic age, the baroque fostered the rise of national schools that produced artistic giants like Bernini, Caravaggio, Rubens, Rembrandt, Velázquez, Claude, Poussin, Tiepolo, and Guardi. The masterpieces of these and other artists reflect the wide variety of baroque art and will be studied within the context of certain commonly held ideals and of the differing economic, political, and religious systems that characterized the period. Not offered 2015–16.

Art 51. European Art of the 18th Century: From the Rococo to the Rise of Romanticism. *9 units (3-0-6); third term.* The course will encompass 18th-century European painting, sculpture, architecture, and the decorative arts. During this period a variety of styles and subjects proliferated in the arts, as seen in the richly diverse works of artists such as Watteau, Boucher, Chardin, Fragonard, Tiepolo, Canaletto, Hogarth, Gainsborough, Blake, David, Piranesi, and Goya, which reflect a new multiplicity in ways of apprehending the world. Not offered 2015–16.

Art 52. British Art. *9 units (3-0-6), third term.* A survey course on British painting, sculpture, and architecture in the 17th, 18th, and 19th centuries. By examining the works of well-known British artists such as Hogarth, Blake, Gainsborough, Reynolds, Constable, and Turner, the class will focus on the multiplicity of styles and themes that developed in the visual arts in Britain from 1740 to 1840 and are part of the wider artistic phenomenon known as romanticism. This introduction to the British visual arts will be enriched by several class meetings in the Huntington Art Gallery. Instructor: Bennett.

Art 55. Art of the 19th Century. *9 units (3-0-6); third term.* A survey of 19th-century art with an emphasis on French and English art between ca. 1770 and 1880. This course will focus on issues including competing conceptions of the public for art, the rise of photography, the development of the avant-garde, and the place of art in urban culture. Not offered 2015–16.

Art 66. Ancient Art: From the Pyramids to the Colosseum. *9 units (3-0-6); second term.* A survey of the art of the earliest civilization of the ancient near east and Mediterranean from the Bronze Age to A.D. 300. The major monuments—architectural, sculptural, and pictorial—of Mesopotamia, Egypt, the Aegean, Greece, and Rome will be examined as solutions to problems of form and function presented by communal political, economic, and religious life. Emphasis will be placed on the creation of Greco-Roman art, the foundation of the Western artistic tradition. Not offered 2015–16.

Art 67. Italian Renaissance Art. *9 units (3-0-6); first term.* A basic study of the greatest achievements of Italian painting, sculpture, and architecture in the 15th and 16th centuries. Masterpieces by a succession of artists such as Giotto, Masaccio, Brunelleschi, Donatello, Alberti, the Bellini, Leonardo da Vinci, Michelangelo, Raphael, Titian, Veronese, and others will be examined for their formal beauty and power, and studied as manifestations of individual genius in the context of their time and place: Italy, fragmented politically, yet at the peak of its cultural dominance. Not offered 2015–16.

Art/H 68. Modern Art. *9 units (3-0-6); first term.* The purpose of this course is to give students a broad view of the history and significance of Western art in the 19th and 20th centuries. We will focus on the impact that shifts in production and social relations—generally referred to as "modernization"—had on culture from 1850-1950. Through close readings of primary and secondary texts, we will unpack some of the modernist period's most influential developments, such as the relation between industrial and cultural production, the seeming contest between mass and avant-garde culture, and utopian cultural theories. The course aims to provide students with an understanding and appreciation of the history of modernist art in the West, as well as the tools with which to write about visual culture analytically. Not offered 2015–16.

Art/H 69. Modernism in the Visual Arts, 1850-1945. *9 units (3-0-6); second term.* This course examines European and American painting, sculpture, photography, and other visual arts from 1850 to the mid-twentieth century. An era encompassing many diverse and significant developments in modern art, this period includes Impressionism, Post-Impressionism, Symbolism, Expressionism, Cubism, Dada, Surrealism, and Abstract Expressionism. Artworks from these movements will be studied in light of their social, cultural, and political contexts, with particular attention paid to issues of gender and representation, and to the different forms of abstraction developed and theorized by early twentieth-century painters. The class will also focus on the relationships of colonialism, urbanism, rising industrialism, and international conflict to the visual culture of the period. Not offered 2015–16.

Art 70. Traditions of Japanese Art. *9 units (3-0-6), first term.* An introduction to the great traditions of Japanese art from prehistory through the Meiji Restoration (1868–1912). Students will examine major achievements of sculpture, painting, temple architecture, and ceramics as representations of each artistic tradition, whether native or adapted from foreign sources. Fundamental problems of style and form will be discussed, but aesthetic analysis will always take place within the conditions created by the culture. Not offered 2015-15.

Art 71. Arts of Buddhism. *9 units (3-0-6); second term.* An examination of the impact of Buddhism on the arts and cultures of India, Southeast Asia, China, Korea, and Japan from its earliest imagery in the 4th century B.C.E. India through various doctrinal transformations to the Zen revival of 18th-century Japan. Select monuments of Buddhist art, including architecture, painting, sculpture, and ritual objects, will serve as focal points for discussions on their aesthetic principles and for explorations into the religious, social, and cultural contexts that underlie their creation. Instructor: Wolfgram.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6).* For course description, see Engineering.

H/Art 119. Art Worlds. *9 units (3-0-6).* For course description, see History.

Art/H 153. The Politics of Representation in American Art, 1935-2000. *9 units (3-0-6); first term.* This course examines major historical concerns and artistic themes in American Art from 1935, the advent of the Popular Front, to the end of the 20th century, the heart of post-modernism. We shall read art historical and theoretical texts so as to understand the role of art in the formation of American identity. In addition to familiarizing students with a broad range of themes within the history of American art, this course will analyze the relation between art and broader social and political contexts. Not offered 2015-15.

Art/H 154. Art and Technology. *9 units (3-0-6); third term.* From perceptual experiments in abstract art to hacktivism and neuroaesthetics, this course explores interactions and interventions between art and technology from the 1960s to the present. Our focus will be on artists and artists groups working in the last forty years who have taken developments in science and technology as their primary subject of inquiry and critique. Topics include experiments in perceptual technology, land use, scientific representations, bio-art, net.art and data use. Students will engage in a research project that focuses on a recent collaboration between art and science. Not offered 2015–16.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6); first term.* This course examines interactions between art, science, and technological innovation in Europe and its colonies ca. 1500–1750. It will explore influential arguments that have linked the growth of empiricism in the sciences to naturalism in early modern visual art. Major topics may include the place of artistic training in scientific discovery, the "maker's knowledge" tradition, and relations of mind to body in early modern visual culture. Objects and images from local collections will be central to analysis. Not offered 2015–16.

Art 169. The Arts of Dynastic China. *9 units (3-0-6); first term.* A survey of the development of Chinese art in which the major achievements in architecture, sculpture, painting, calligraphy, and ceramics will be studied in their cultural contexts from prehistory through the Manchu domination of the Qing Dynasty (1644–1911). Emphasis will be placed on the aesthetic appreciation of Chinese art as molded by the philosophies, religions, and history of China. Instructor: Wolfgram.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. *9 units (3-0-6); first term.* This course examines the ways in which spectacle has been used in early modern and nineteenth-century Europe. Drawing on aesthetic writings about the impact of size and scale on audiences, but also examining historical accounts of the workings of spectacle on spectators, it looks at a number of case studies focusing on the technologies spectacles employed, the sites at which they were staged, the purposes and aims of their creators, and the controversies they engendered. Topics covered include English court masques, the rituals of absolute monarchy (especially those of Louis XIV), the changing presentation of plays and works of art, the public exhibition of torture, punishment, and human dissection, cabinets of curiosity and scientific demonstrations, religious, civic, and political ritual commemoration, the development of mixed media, panoramas and dioramas, and the staging of international exhibitions. Not offered 2015–16.

ASTROPHYSICS

Ay 1. The Evolving Universe. *9 units (3-3-3); third term; This course is intended primarily for freshmen not expecting to take more advanced astronomy courses and will satisfy the menu requirement of the Caltech core curriculum.* Introduction to modern astronomy that will illustrate the accomplishments, techniques, and scientific methodology of contemporary astronomy. The course will be organized around a set of basic questions, showing how our answers have changed in response to fresh observational discoveries. Topics to be discussed will include telescopes, stars, planets, the search for life elsewhere in the universe, supernovae, pulsars, black holes, galaxies and their active nuclei, and Big Bang cosmology. This class will be offered in a "flipped classroom" mode: the students will be required to watch the video lectures first, and then discuss them and work out problems in the classroom. A field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Djorgovski.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. *6 units (2-0-4); second term.* For course description, see Freshman Seminar.

Ge/Ay 11 c. Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 20. Basic Astronomy and the Galaxy. *10 units (3-1-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc or instructor's permission.* The electromagnetic spectrum and basic radiative transfer; ground and space observing techniques; "pictorial Fourier description" of astrophysical optics; Kepler's laws; exoplanets; stellar masses, distances, and motions; the birth, structure, evolution, and death of stars; the structure and dynamics of the Galaxy. Lessons will emphasize the use of order-of-magnitude calculations and scaling arguments in order to elucidate the physics of astrophysical phenomena. Short labs will introduce astronomical measurement techniques. Instructor: Hillenbrand.

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); second term. Prerequisites: Ma 1 abc, Ph 1 abc or instructor's permission.* Cosmological models and parameters, extragalactic distance scale, cosmological tests; constituents of the universe, dark matter, and dark energy; thermal history of the universe, cosmic nucleosynthesis, recombination, and cosmic microwave background; formation and evolution of structure in the universe; galaxy clusters, large-scale structure and its evolution; galaxies, their properties and fundamental correlations; formation and evolution of galaxies, deep surveys; star formation history of the universe; quasars and other active galactic nuclei, and their evolution; structure and evolution of the intergalactic medium; diffuse extragalactic backgrounds; the first stars, galaxies, and the reionization era. Instructor: Djorgovski

Ay 30. Introduction to Modern Research. *3 units (2-0-1); second term.* Weekly seminar open to declared Ay majors at the discretion of the instructor; nonmajors who have taken astronomy courses may be admitted. Course is intended for sophomores and juniors. This seminar is held in faculty homes in the evening and is designed to encourage student communication skills as they are introduced to faculty members and their research. Each week a student will review a popular-level article in astronomy for the class. Graded pass/fail. Instructor: Cohen.

Ay 31. Writing in Astronomy. *3 units (1-0-2); third term.* This course is intended to provide practical experience in the types of writing expected of professional astronomers. Example styles include research proposals, topical reviews, professional journal manuscripts, and articles for popular magazines such as Astronomy or Sky and Telescope. Each student will adopt one of these formats in consultation with the course instructor and write an original piece. An outline and several drafts reviewed by both a faculty mentor familiar with the topic and the course instructor are required. This course is most suitable for juniors and seniors. Fulfills the Institute scientific writing requirement. Instructor: Hillenbrand.

Ay 43. Reading in Astronomy and Astrophysics. *Units in accordance with work accomplished, not to exceed 3.* Course is intended for students with a definite independent reading plan or who attend regular (biweekly) research and literature discussion groups. Instructor's permission required. Graded pass/fail. Instructor: Staff.

Ay 78 abc. Senior Thesis. *9 units. Prerequisite: To register for this course, the student must obtain approval of the astronomy option representative and the prospective thesis adviser.* Previous SURF or independent study work can be useful experience. Course is open to senior astronomy majors only. Research must be supervised by a faculty member. Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the astronomy option representative. The student will work with an advisor to formulate a research project, conduct original research, present new results, and evaluate them in the context of previously published work in the field. The first two terms are graded pass/fail and the grades are then changed at the end of the course to the appropriate letter grade for all three terms. In order to receive a passing grade for second term, a work plan and a preliminary thesis outline must be submitted. The written thesis of 20–100 pages must be completed and approved by the adviser and the option representative before the end of the third term. Instructor: Staff.

Ay 101. Physics of Stars. *11 units (3-2-6); first term. Prerequisite: Ay 20 is recommended.* Physics of stellar interiors and atmospheres. Properties of stars, stellar spectra, radiative transfer, line formation. Stellar structure, stellar evolution. Nucleosynthesis in stars. Stellar oscillations. Instructor: Cohen.

Ay 102. Physics of the Interstellar Medium. *9 units (3-0-6); second term. Prerequisite: Ay 20 is recommended.* An introduction to observations of the inter-stellar medium and relevant physical processes. The structure and hydrodynamic evolution of ionized hydrogen regions associated with massive stars and supernovae, thermal balance in neutral and ionized phases, star formation and global models for the interstellar medium. Instructor: Kulkarni.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 1, Ph 2 ab.* This course is designed primarily for junior and senior undergraduates in astrophysics and physics. It covers the physics of black holes and neutron stars, including accretion, particle acceleration and gravitational waves, as well as their observable consequences: (neutron stars) pulsars, magnetars, X-ray binaries, gamma-ray bursts; (black holes) X-ray transients, tidal disruption and quasars/active galaxies and sources of gravitational waves. Instructor: Kasliwal.

Ay 105. Optical Astronomy Instrumentation Lab. *10 units (0-6-4); second term. Prerequisite: Ay 20.* An opportunity for astronomy and physics undergraduates (juniors and seniors) to gain firsthand experience with the basic instrumentation tools of modern optical and infrared astronomy. The 10 weekly lab experiments are expected to include radiometry measurements, geometrical optics, optical aberrations and ray tracing, spectroscopy, fiber optics, CCD electronics, CCD characterization, photon counting detectors, vacuum and cryogenic technology, and stepper motors and encoders. Instructors: Hallinan, Mawet.

Ay 111 a. Introduction to Current Astrophysics Research. *3 units; first term.* This course is intended primarily for first-year Ay graduate students, although participation is open and encouraged. Students are required to attend seminar-style lectures given by astrophysics faculty members, describing their research, to attend the weekly astronomy colloquia, and to follow these with additional readings on the subject. At the end of each term, students are required to summarize in oral or written form (at the discretion of the instructor), one of the covered subjects that is of most interest to them. Instructor: Hallinan.

Ge/Ay 117. Statistics and Data Analysis. *9 units (3-0-6); third term. Prerequisites: CS 1 and instructor's permission.* For course description, see Geological and Planetary Sciences.

Ay 119. Methods of Computational Science. *9 units (3-0-6); third term.* Open to graduate and upper-division undergraduate students in all options. Practical computational science methods useful in disciplines dealing with large and/or complex data sets. Topics include: Scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. Instructor: Djorgovski.

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisite: Ph 125 or equivalent (undergraduates).* The interaction of radiation with matter: radiative transfer, emission, and absorption. Compton processes, coherent emission processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructors: Hallinan, Kirby.

Ay 122 abc. Astronomical Measurements and Instrumentation. *9 units (3-0-6); in 2015–16, only 122 a is offered, first term. Prerequisite: Ph 106 or equivalent.* Telescopes, optics, detectors, radiometers, photometry, spectroscopy. Active/adaptive optics. Interferometers/arrays. Imaging devices and image processing. Antennae, receivers, mixers, and amplifiers. Space telescopes. Signal analysis techniques and probability and statistics as relevant to astronomical measurement. Some lab work and observatory field trips. Ay 122 a concentrates on infrared, optical, and ultraviolet techniques. Ay 122 b (not offered 2015–16) concentrates on radio through submillimeter techniques, and Ay 122 c (not offered 2015–16) concentrates on X-ray through gamma-ray techniques. Instructors: (a) Steidel, Mawet.

Ay 123. Structure and Evolution of Stars. *9 units (3-0-6); second term. Prerequisites: Ay 101; Ph 125 or equivalent (undergraduates).* Thermodynamics, equation of state, convection, opacity, radiative transfer, stellar atmospheres, nuclear reactions, and stellar models. Evolution of low- and high-mass stars, supernovae, and binary stars. Instructors: Kirby.

Ay 124. Structure and Dynamics of Galaxies. *9 units (3-0-6); second term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Stellar dynamics and properties of galaxies; kinematics and dynamics of our galaxy; spiral structure; stellar composition, masses, and rotation of external galaxies; star clusters; galactic evolution; binaries, groups, and clusters of galaxies. Instructor: Steidel.

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 106 and Ph 125 or equivalent (undergraduates).* High-energy astrophysics, the final stages of stellar evolution; supernovae, binary stars, accretion disks, pulsars; extragalactic radio sources; active galactic nuclei; black holes. Instructor: Phinney.

Ay 126. Interstellar and Intergalactic Medium. *9 units (3-0-6); second term. Prerequisite: Ay 102 (undergraduates).* Physical processes in the interstellar medium. Ionization, thermal and dynamic balance of interstellar medium, molecular clouds, hydrodynamics, magnetic fields, H II regions, supernova remnants, star formation, global structure of interstellar medium. Instructor: Hopkins.

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); third term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Cosmology; extragalactic distance determinations; relativistic cosmological models; galaxy formation and clustering; thermal history of the universe, microwave background; nucleosynthesis; cosmological tests. Instructor: Hopkins.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6); second term.* For course description, see Geological and Planetary Sciences.

Ay 141 abc. Research Conference in Astronomy. *3 units (1-0-2); first, second, third terms.* Oral reports on current research in astronomy, providing students an opportunity for practice in the organization and presentation of technical material. A minimum of two presentations will be expected from each student each year. In addition, students are encouraged to participate in a public-level representation of the same material for posting to an outreach website. This course fulfills the option communication requirement and is required of all astronomy graduate students who have passed their preliminary exams. It is also recommended for astronomy seniors. Graded pass/fail. (a) Hopkins, Kirby; (b) Cohen, Mawet; (c) Kasliwal, Phinney.

Ay 142. Research in Astronomy and Astrophysics. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of research outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy for graduate students. Graded pass/fail.

Ay 143. Reading and Independent Study. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of reading and independent study outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy for graduate students. Graded pass/fail.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 190. Computational Astrophysics. *9 units (3-0-6); second term. Prerequisites: Ph 20–22 (undergraduates).* Introduction to essential numerical analysis and computational methods in astrophyics and astrophysical data analysis. Basic numerical methods and techniques; N-body simulations; fluid dynamics (SPH/grid-based); MHD; radiation transport; reaction networks; data analysis methods; numerical relativity. Not offered 2015–16.

Ay/Ge 198. Special Topics in the Planetary Sciences. *9 units (3-0-6); third term.* Topic for 2015–16 is Extrasolar Planets. Thousands of planets have been identified in orbit around other stars. Astronomers are now embarking on understanding the statistics of extrasolar planet populations and characterizing individual systems in detail, namely star-planet, planet-planet and planet-disk dynamical interactions, physical parameters of planets and their composition, weather phenomena, etc. Direct and indirect detection techniques are now completing the big picture of extra-solar planetary systems in all of their natural diversity. The seminar-style course will review the state of the art in exoplanet science, take up case studies, detail current and future instrument needs, and anticipate findings. Instructors: Batygin, Hillenbrand, Mawet.

Ay 211. Contemporary Extragalactic Astronomy. *9 units (3-0-6); third term. Prerequisites: Ay 123, Ay 124, and Ay 127.* Topics in extragalactic astronomy and cosmology, including observational probes of dark matter and dark energy; cosmological backgrounds and primordial element abundances; galaxy formation and evolution, including assembly histories, feedback and environmental effects; physics of the intergalactic medium; the role of active galactic nuclei; galactic structure and stellar populations; future facilities and their likely impact in the field. Not offered 2015–2016.

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term.* Course for graduate students and seniors in astronomy and planetary science. Students will be required to lead some discussions. Topic will be selected based on student interest. Not offered 2015–16.

Ay 218. Extrasolar Planets. *9 units (3-0-6); third term.* Extrasolar Planets. For 2015–16, this course is being offered as Ay/Ge 198.

Ay 219. Elements in the Universe and Galactic Chemical Evolution. *9 units (3-0-6); second term. Prerequisites: Ay 121, 123, 124, 126.* Survey of the formation of the elements in the universe as a function of cosmic time. Review of the determination of abundances in stars, meteorites, H II regions, and in interstellar and intergalactic gas. Overview of models of galactic chemical evolution. Participants will measure elemental abundances from the Keck spectrum of a star and construct their own numerical chemical evolution models. Not offered 2015–16.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3- 0-6); first.* P*rerequisites: Bi/Ch 110.* Detailed analysis of the structures of the four classes of biological molecules and the forces that shape them. Introduction to molecular biological and visualization techniques. Instructors: Clemons.

BMB/Bi/Ch 173. Biophysical/Structural Methods. *9 units (3-0-6); second.* Basic principles of modern biophysical and structural methods used to interrogate macromolecules from the atomic to cellular levels, including light and electron microscopy, X-ray crystallography, NMR spectroscopy, single molecule techniques, circular dichroism, surface plasmon resonance, mass spectrometry, and molecular dynamics and systems biological simulations. Instructors: Clemons, Grant, and other guest lecturers

BMB/Bi/Ch 174. Molecular Machines in the Cell. *9 units (3-0-6); third. Prerequisites: Bi/Ch 110, BMB/Bi/Ch 170, BMB/Bi/Ch 173.* Detailed analysis of specific macromolecular machines and systems that illustrate the principles and biophysical methods taught in BMB/Bi/Ch 170 and BMB/Bi/Ch 173. Instructors: Shan, Hoelz and various guest lecturers (subject to change each year).

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. *9 units (3-0-6); first term. Prerequisites: Bi/Ch 110 or equivalent.* Discussion of the energetic principles and molecular mechanisms that underlie enzyme's catalytic proficiency and exquisite specificity. Principles of allosteric regulation, selectivity, enzyme evolution, and computational enzyme design. Practical kinetics sections discuss how to infer molecular mechanisms from rate/equilibrium measurements and their application to more complex biological systems, including steady-state and pre-steady-state kinetics, kinetic simulations, and kinetics at the single molecule resolution. Instructors: Shan.

BMB/Ch 202 abc. Biochemistry Seminar Course. *1 unit; first, second, third terms.* A course that includes a seminar on selected topics from outside faculty on recent advances in biochemistry. Students will participate in the seminar along with a formal discussion section with visiting faculty. Students will meet with the Biochemistry seminar speaker in the discussion section for an hour, and then attend the Biochemistry seminar at 4 p.m. BMB Seminars take place 1-2 times per month (usually on Thursdays).

BMB/Ch 230. Macromolecular Structure Determination with Modern X-ray Crystallography Methods. *12 units (2-4-6); third term. Prerequisites: BMB/Bi/Ch 170 and consent of instructor.* Advanced course in macromolecular crystallography integrating lecture and laboratory treatment of diffraction theory, crystallization (proteins, nucleic acids and macromolecular complexes), crystal characterization, X-ray sources and optics, crystal freezing, X-ray diffraction data collection (in-house and synchrotron), data reduction, multiple isomorphous replacement, single- and multi-wavelength anomalous diffraction phasing techniques, molecular replacement, electron density interpretation, structure refinement, structure validation, coordinate deposition and structure presentation. In the laboratory component, one or more proteins will be crystallized and the structure(s) determined by several methods, in parallel with lectures on the theory and discussions of the techniques Instructors: Hoelz.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit.* For course description, see Biology.

BMB 278. Fundamentals of Molecular Genetics. *9 units (3-0-6); third term.* Principles and mechanisms of DNA repair and replication, transcription and splicing, and protein synthesis. Not offered 2015–16.

BMB 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BIOENGINEERING

BE 1. Frontiers in Bioengineering. *1 unit; second term.* A weekly seminar series by Caltech faculty providing an introduction to research directions in the field of bioengineering. Required for BE undergraduates. Graded pass/fail. Instructor: Staff.

Bi/BE 24. Technical Communication for Biological Scientists and Engineers. *6 units (3-0-3); first, third terms.* For course description, see Biology.

BE 98. Undergraduate Research in Bioengineering. *Variable units, as arranged with the advising faculty member; first, second, third terms.* Undergraduate research with a written report at the end of each term; supervised by a Caltech faculty member, or coadvised by a Caltech faculty member and an external researcher. Graded pass/fail. Instructor: Staff.

BE/Bi 101. Order of Magnitude Biology. *6 units (3-0-3); third term. Prerequisites: none.* In this course, students will develop skills in the art of educated guesswork and apply them to the biological sciences. Building from a few key numbers in biology, students will "size up" biological systems by making inferences and generating hypotheses about phenomena such as the rates and energy budgets of key biological processes. The course will cover the breadth of biological scales: molecular, cellular, organismal, communal, and planetary. Undergraduate and graduate students of all levels are welcome. Instructors: Bois, Phillips. Offered alternate years; offered 2015–16.

BE/Bi 103. Data Analysis in the Biological Sciences. *9 units (1-3-5); first term. Prerequisites: CS 1 or equivalent; Bi 1, Bi 1x, Bi 8, or equivalent; or instructor's permission.* This course covers a basic set of tools needed to analyze quantitative data in biological systems, both natural and engineered. Students will analyze real data in class and in homework. Python will be used as the programming language of instruction. Topics will include regression, parameter estimation, outlier detection and correction, error estimation, image processing and quantifcation, denoising, hypothesis testing, and data display and presentation. Instructor: Bois.

BE/Bi/MedE 106. Introduction to Biomechanics. *9 units (3-0-6); third term.* Introduction to the basic concepts of applying engineering principles of solid and fluid mechanics to the study of biological systems. The course emphasizes the organismal, rather than the molecular, level of complexity. It draws on a wide array of biological phenomena from plants and animals, and is not intended as a technical introduction to medically related biomechanics. Topics may include fundamental properties of solids and fluids, viscoelasticity, drag, biological pumps, locomotion, and muscle mechanics. Not offered 2015–16.

BE 107. Exploring Biological Principles Through Bio-Inspired Design. *9 units (3-5-1); third term. Prerequisites: None.* Students will formulate and implement an engineering project designed to explore a biological principle or property that is exhibited in nature. Students will work in small teams in which they build a hardware platform that is motivated by a biological example in which a given approach or architecture is used to implement a given behavior. Alternatively, the team will construct new experimental instruments in order to test for the presence of an engineering principle in a biological system. Example topics include bio-inspired control of motion (from bacteria to insects), processing of sensory information (molecules to neurons), and robustness/fault-tolerance. Each project will involve proposing a specific mechanism to be explored, designing an engineering system that can be used to demonstrate and evaluate the mechanism, and building a computer-controlled, electro-mechanical system in the lab that implements or characterizes the proposed mechanism, behavior or architecture. Instructors: Dickinson, Murray.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6); second term.* For course description, see Chemical Engineering.

Ph/APh/EE/BE 118 ab. Physics of Measurement. *9 units (3-0-6); first and second terms.* For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. *9 units (3-0-6); third terms.* For course description, see Physics.

BE 150. Design Principles of Genetic Circuits. *9 units (3-0-6); third term. Prerequisites: none.* Quantitative studies of cellular and developmental systems in biology, including the architecture of specific genetic circuits controlling microbial behaviors and multicellular development in model organisms. Specific topics include chemotaxis, multistability and differentiation, biological oscillations, stochastic effects in circuit operation, as well as higher-level circuit properties such as robustness. Organization of transcriptional and protein-protein interaction networks at the genomic scale. Topics are approached from experimental, theoretical and computational perspectives. Instructors: Bois, Elowitz.

BE 153. Case Studies in Systems Physiology. *9 units (3-0-6); third term. Prerequisites: Bi 8, Bi 9, or equivalent*. This course will explore the process of creating and validating theoretical models in systems biology and physiology. It will examine several macroscopic physiological systems in detail, including examples from immunology, endocrinology, cardiovascular physiology, and others. Emphasis will be placed on understanding how macroscopic behavior emerges from the interaction of individual components. Instructor: Petrasek.

Bi/NB/BE 155. Neuropharmacology. *6 units (3-0-3); second term.* For course description, see Biology.

BE 159. Signal Transduction and Mechanics in Morphogenesis. *9 units (3-0-6); second term. Prerequisites: Bi 8, Bi 9, ACM 95 ab, or instructor's permission.* This course examines the mechanical and biochemical pathways that govern morphogenesis. Topics include embryonic patterning, cell polarization, cell-cell communication, and cell migration in tissue development and regeneration. The course emphasizes the interplay between mechanical and biochemical pathways in morphogenesis. Instructor: Bois.

BE/APh 161. Physical Biology of the Cell. *12 units (3-0-9); second term. Prerequisites: Ph 2ab and ACM 95abc, or background in differential equations and statistical and quantum mechanics, or instructor's written permission.* Physical models applied to the analysis of biological structures ranging from individual proteins and DNA to entire cells. Topics include the force response of proteins and DNA, models of molecular motors, DNA packing in viruses and eukaryotes, mechanics of membranes, and membrane proteins and cell motility. Instructor: Bois.

ChE/BE 163. Introduction to Biomolecular Engineering. *12 units (3-0-9); first term.* For course description, see Chemical Engineering.

EE/BE/MedE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5).* For course description, see Electrical Engineering.

BE 167. Research Topics in Bioengineering. *1 unit; first term.* Introduction to current research topics in Caltech bioengineering labs. Graded pass/fail. Instructor: Staff.

BE 168. Reading the Bioengineering Literature. *4 units (1-0-3); second term. Prerequisites: None.* Participants will read, discuss, and critique papers on diverse topics within the bioengineering literature. *Enrollment limited to 10 students; undergraduates with instructor's permission.* Instructor: Winfree. Offered in alternate years; not offered 2015–16.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6); second term.* For course description, see Biology.

Bi/BE 182. Animal Development and Genomic Regulatory Network Design. *9 units (3-0-6); second term.* For course description, see Biology.

EE/BE/MedE 185. MEMS Technology and Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

ChE/BE/MedE 188. Molecular Imaging. *9 units (3-0-6); second term.* For course description see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. *12 units (3-6-3) a = first and second terms; 9 units (0-9-0) b = second term. Prerequisites: ACM 95 ab (for BE/EE/MedE 189 a); BE/EE/MedE 189 a (for BE/EE/MedE 189 b).* Part a, students will design and implement biosensing systems, including a pulse monitor, a pulse oximeter, and a real-time polymerase-chain-reaction incubator. Students will learn to program in LABVIEW. Part b is a student-initiated design project requiring instructor's permission for enrollment. Enrollment is limited to 24 students. BE/EE/MedE 189 a is an option requirement; BE/EE/MedE 189 b is not. Instructor: Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6) second term; (2-4-3) third term. Prerequisite: none. Recommended: ChE/BE 163, CS 21, CS 129 ab, or equivalent.* This course investigates computation by molecular systems, emphasizing models of computation based on the underlying physics, chemistry, and organization of biological cells. We will explore programmability, complexity, simulation of and reasoning about abstract models of chemical reaction networks, molecular folding, molecular self-assembly, and molecular motors, with an emphasis on universal architectures for computation, control, and construction within molecular systems. If time permits, we will also discuss biological example systems such as signal transduction, genetic regulatory networks, and the cytoskeleton; physical limits of computation, reversibility, reliability, and the role of noise, DNA-based computers and DNA nanotechnology. Part a develops fundamental results; part b is a reading and research course: classic and current papers will be discussed, and students will do projects on current research topics. Instructor: Winfree.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. *a = 12 units (3-6-3) second term; b = 12 units (2-8-2) third term. Prerequisites: ChE/BE 163 or BE/CS/CNS/Bi 191a, or instructor's permission.* This course will introduce students to the conceptual frameworks and tools of computer science as applied to molecular engineering, as well as to the practical realities of synthesizing and testing their designs in the laboratory. In part a, students will design and construct DNA logic circuits, biomolecular neural networks, and complex two-dimensional and three-dimensional nanostructures, as well as quantitatively analyze the designs and the experimental data. Students will learn laboratory techniques including gel electrophoresis, fluorescence spectroscopy, and atomic force microscopy, and will use software tools and program in Mathematica or Mat lab. Part b is an open-ended, design-and-build project requiring instructor's permission for enrollment. Enrollment in both parts a and b is limited to 12 students. Instructor: Qian.

BE 200. Research in Bioengineering. *Units and term to be arranged.* By arrangement with members of the staff, properly qualified graduate students are directed in bioengineering research.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units; summer. Prerequisites: none.* This course provides an intensive, hands-on, pragmatic introduction to computer programming aimed at biologists and bioengineers. No previous programming experience is assumed. Python is the language of instruction. Students will learn basic concepts such as data types, control structures, string processing, functions, input/output, etc., while writing code applied to biological problems. At the end of the course, students will be able to perform simple simulations, write scripts to run software packages and parse output, and analyze and plot data. This class is offered as a week long "boot camp," starting two weeks before the start of the fall term, in which students spend all day working on the course. Graded pass/fail. Instructors: Bois, Guttman.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4); second term.* For course description, see Biology.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. *9 units (3-2-4); third term.* For course description, see Biology.

BE 240. Special Topics in Bioengineering. *Units and term to be arranged.* Topics relevant to the general educational goals of the bioengineering option. Graded pass/fail.

Ae/BE 242. Biological Flows: Propulsion. *9 units (3-0-6).* For course description, see Aerospace.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6); second term.* For course description, see Medical Engineering.

BIOLOGY

Bi 1. Principles of Biology. *9 units (4-0-5); third term.* Advances in biotechnology have driven unprecedented integration across the hierarchy of biology, from molecules to ecosystems, as well as the integration of biology with other sciences, including geology, physics, chemistry and mathematics. The design of this biology course seeks to provide introductory students with a strong foundation built on a set of basic principles that will provide students with the intellectual tools for critical thinking in the discipline. Because the microbial world has been critical in all aspects of biology, from the environmental to human health, throughout the evolution of the biosphere, a microbiological perspective will form the nucleus around which each major topic will be developed. Specifically, we will discuss key concepts in cellular and molecular biology (e.g. cytoskeletal elements, transcription, translation), ecology, evolution, and metabolism (e.g. biosynthesis and energy generation) by providing examples from the microbial world. Instructor: Newman.

Bi 1 x. The Great Ideas of Biology: Exploration through Experimentation. *9 units (0-6-3); third term.* Introduction to concepts and laboratory methods in biology. Molecular biology techniques and advanced microscopy will be combined to explore the great ideas of biology. This course is intended for nonbiology majors and will satisfy the freshman biology course requirement. Limited enrollment. Instructor: Bois.

Bi 2. Current Research in Biology. *3 units (1-0-2); first term. Intended for students considering the biology option; open to freshmen.* Current research in biology will be discussed, on the basis of reading assigned in advance of the discussions, with members of the divisional faculty. Graded pass/fail. Instructor: Elowitz.

Bi 8. Introduction to Molecular Biology: Organization and Expression of Genetic Information. *9 units (4-0-5); second term.* This course and its sequel, Bi 9, cover biology at the molecular and cellular levels. Bi 8 emphasizes genomic structure and mechanisms involved in the organization and regulated expression of genetic information. The focus is on the ways that the information content of the genome is translated into distinctive, cell type specific patterns of gene expression and protein function, with special attention to the problems of gene regulation in complex multicellular organisms. Assignments will include critical dissections of papers from current research literature and individual oral presentations by students to the class on specific topics. Instructor: Rothenberg.

Bi 9. Cell Biology. *9 units (3-0-6); third term.* Continues coverage of biology at the cellular level, begun in Bi 8. Topics: cytoplasmic structure, membrane structure and function, cell motility, and cell-cell recognition. Emphasis on both the ultrastructural and biochemical approaches to these topics. Instructors: Aravin, Deshaies.

Bi 10. Introductory Biology Laboratory. *6 units (1-3-2); third term. Prerequisites: Bi 8; designed to be taken concurrently with Bi 9.* An introduction to molecular, cellular, and biochemical techniques that are commonly used in studies of biological systems at the molecular level. Instructor: Staff.

FS/Bi 13. In Search of Memory. *6 units (2-0-4).* For course description, see Freshman Seminar.

Bi 22. Undergraduate Research. *Units to be arranged; first, second, third terms.* Special problems involving laboratory research in biology; to be arranged with instructors before registration. Graded pass/fail. Instructor: Staff.

Bi 23. Biology Tutorials. *3 or 6 units; second term.* Small group study and discussion in depth of special areas or problems in biology, involving regular tutorial sections with instructors drawn from the divisional postdoctoral staff and others. Usually given winter term. To be arranged with instructors before registration. Graded pass/fail. Instructor: Huang.

Bi/BE 24. Technical Communication for Biological Scientists and Engineers. *6 units (3-0-3); first, third terms.* This course offers instruction and practice in writing and speaking relevant to professional biological scientists and engineers working in research, teaching, and/or medical careers. Students will write a paper for a scientific or engineering journal, either based on their previous research or written as a review paper of current work in their field. A Caltech faculty member, a postdoctoral scholar, or technical staff member serves as a technical mentor for each student, to provide feedback on the content and style of the paper. Oral presentations will be based on writing produced in the course, with feedback from instructors and peers. Fulfills the Institute scientific writing requirement. Instructor: Staff.

Bi 90 abc. Undergraduate Thesis. *12 or more units per term; first, second, third terms. Prerequisites: 18 units of Bi 22 (or equivalent research experience) in the research area proposed for the thesis, and instructor's permission.* Intended to extend opportunities for research provided by Bi 22 into a coherent individual research project, carried out under the supervision of a member of the biology faculty. Normally involves three or more consecutive terms of work in the junior and senior years. The student will formulate a research problem based in part on work already carried out, evaluate previously published work in the field, and present new results in a thesis format. First two terms graded pass/fail; final term graded by letter on the basis of the completed thesis. Instructor: Bjorkman.

BE/Bi 101. Order of Magnitude Biology. *6 units (3-0-3); second term.* For course description, see Bioengineering.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/Bi 103. Data Analysis in the Biological Sciences. *9 units (1-3-5); first term.* For course description, see Bioengineering.

Bi/Ge/ESE 105. Evolution. *12 units (3-4-5); second term. Prerequisites: Completion of Core Curriculum Courses. Maximum enrollment: 15, by application only.* The theory of evolution is arguably biology's greatest idea and serves as the overarching framework for thinking about the diversity and relationships between organisms. This course will present a broad picture of evolution starting with discussions of the insights of the great naturalists, the study of the genetic basis of variation, and an introduction to the key driving forces of evolution. Following these foundations, we will then focus on a number of case studies including the following: evolution of oxygenic photosynthesis, origin of eukaryotes, multicellularity, influence of symbiosis, the emergence of life from the water (i.e. fins to limbs), the return of life to the water (i.e. limbs to fins), diversity following major extinction events, the discovery of Archaea, insights into evolution that have emerged from sequence analysis, and finally human evolution and the impact of humans on evolution (including examples such as antibiotic resistance). A specific focus for considering these issues will be the island biogeography of the Galapagos. Instructors: Phillips, Orphan. Given in alternate years; offered 2015–16.

BE/Bi/MedE 106. Introduction to Biomechanics. *9 units (3-0-6); third term.* For course description, see Bioengineering.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8); first term. Prerequisite: Ch 41 abc or instructor's permission.* Lectures and recitation introducing the molecular basis of life processes, with emphasis on the structure and function of proteins. Topics will include the derivation of protein structure from the information inherent in a genome, biological catalysis, the intermediary metabolism that provides energy to an organism, and the use of DNA manipulations, cloning, and expression of proteins in foreign hosts to study protein structure and function. Instructor: Biochemistry faculty.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8); second term. Prerequisites: Bi/Ch 110; Bi 8 and Bi 122 recommended.* Lectures and recitation on the molecular basis of biological structure and function. Emphasizes the storage, transmission, and expression of genetic information in cells. Specific topics include DNA replication, recombination, repair and mutagenesis, transcription, RNA processing, and protein synthesis. Instructors: Campbell, Parker.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8); third term. Prerequisites: Bi/Ch 110; Bi 9 recommended or consent of instructor.* Lectures and recitation on the biochemistry of basic cellular processes in the cytosol and organelles, with emphasis on membrane and protein trafficking. Specific topics include protein secretion, virus entry, endocytosis, endoplasmic reticulum dynamics, nuclear trafficking, autophagy, apoptosis, and mitochondrial dynamics. The relationship of these processes to human disease will be discussed. Instructors: Chan, Hoelz.

Bi 114. Immunology. *9 units (3-0-6); second term. Prerequisites: Bi 8, Bi 9, Bi 122 or equivalent, and Bi/Ch 110 recommended.* The course will cover the molecular and cellular mechanisms that mediate recognition and response in the mammalian immune system. Topics include cellular and humoral immunity, the structural basis of immune recognition, antigen presentation and processing, gene rearrangement of lymphocyte receptors, cytokines and the regulation of cellular responses, T and B cell development, and mechanisms of tolerance. The course will present an integrated view of how the immune system interacts with viral and bacterial pathogens and commensal bacteria. Instructors: Mazmanian, Bjorkman.

Bi 115. Attack and Repulsion: Viruses and their Hosts. *9 units (3-0-6); third term.* The course will introduce the chemistry and biology of viruses, emphasizing their diverse replication strategies. It will then focus on mechanisms used by viruses to multiply in the face of host defenses. It will also discuss cancer-inducing viruses. The course will mainly consider mammalian viruses but will also discuss aspects of plant and bacterial viruses. Instructor: Baltimore. Given in alternate years; offered 2015–16.

Bi 117. Developmental Biology. *9 units (3-0-6); second term. Prerequisites: Bi 8 and Bi 9.* A survey of the development of multicellular organisms. Topics will include the beginning of a new organism (fertilization), the creation of multicellularity (cellularization, cleavage), reorganization into germ layers (gastrulation), induction of the nervous system (neurulation), and creation of specific organs (organogenesis). Emphasis will be placed on the molecular mechanisms underlying morphogenetic movements, differentiation, and interactions during development, covering both classical and modern approaches to studying these processes. Instructor: Bronner.

Bi 118. Morphogenesis of Developmental Systems. *6 units (2-0-4); first term. Prerequisites: Bi 8 and Bi 9, and at least one of the following: Bi 117, Bi 122, Bi 129, Bi 145, or Bi/BE 182 (or equivalents).* Discussion of how cells, tissues, and organs take shape: the influence of force on cell shape change; cell migration including chemotaxis and collective cell movement; adhesion/deadhesion during migration; the relationship between cell migration and metastasis; and a review/overview of general signaling principles and embryonic development of invertebrate and vertebrate animals. Class size is limited to 5 students. Given in alternate years; not offered 2015–16.

Bi 122. Genetics. *9 units (3-0-6); first term. Prerequisite: Bi 8 or Bi 9, or instructor's permission.* Lecture and discussion course covering basic principles of genetics. Instructor: Hay.

Bi 129. Biology of Cancer. *9 units (3-0-6); second term.* The first part of the course will concern the basic biology of cancer, covering oncogenes, tumor suppressors, tumor cell biology, metastasis, tumor angiogenesis, and other topics. There will also be a section on cancer genetics, which will primarily be taught from primary literature and journal reviews. The last part of the course will concern treatments, including chemotherapy, anti-angiogenic therapy, and immunotherapy. Textbook: *The Biology of Cancer* (2006) by Robert Weinberg. Given in alternate years; not offered 2015–16.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6); first term. Recommended prerequisite: Bi/Ch 110.* Structural and functional aspects of nucleic acids and proteins, including hybridization; electrophoretic behavior of nucleic acids; principles and energetics of folding of polypeptide chains in proteins; allostery and cooperativity in protein action; enzyme kinetics and mechanisms; and methods of structure determination, such as X-ray diffraction and magnetic resonance. Structure and function of metalloenzymes. Instructors: Beauchamp, Cai.

Bi 145 a. Tissue and Organ Physiology. *9 units (3-0-6); first term.Prerequisites: Bi 8, 9, 110. Bi 110 may be taken concurrently.* Reviews of anatomy and histology, as well as in-depth discussion of cellular physiology. Building from cell function to tissues, the course explores human physiology in an organ-based fashion. First term topics include endocrine physiology, the skeletal system, digestive and hepatic physiology, nutrition and urinary physiology. Particular emphasis is placed on health issues and pharmaceutical therapy from both a research and a medical perspective. Instructor: Tydell.

Bi 145 b. Tissue and Organ Physiology. *9 units (3-0-6); second term. Prerequisites: Bi 145a.* Building on the foundations of Bi 145a, Bi 145b will continue the exploration of human physiology incorporating anatomy and cellular physiology. Topics include muscle physiology, cardiovascular physiology, the respiratory system and reproductive physiology. Particular emphasis is placed on health issues and pharmaceutical therapy from both a research and a medical perspective. Instructor: Tydell.

Bi/CNS/NB 150. Introduction to Neuroscience. *10 units (4-0-6); first term. Prerequisites: Bi 8, 9, or instructors' permission.* General principles of the function and organization of nervous systems, providing both an overview of the subject and a foundation for advanced courses. Topics include the physical and chemical bases for action potentials, synaptic transmission, and sensory transduction; anatomy; development; sensory and motor pathways; memory and learning at the molecular, cellular, and systems level; and the neuroscience of brain diseases. Instructors: Adolphs, Lester.

Bi/CNS/NB 153. Brain Circuits. *9 units (3-0-6); first term. Prerequisites: Bi/CNS/NB 150 or equivalent.* What functions arise when many thousands of neurons combine in a densely connected circuit? Though the operations of neural circuits lie at the very heart of brain science, our textbooks have little to say on the topic. Through an alternation of lecture and discussion this course explores the empirical observations in this field and the analytical approaches needed to make sense of them. We begin with a foray into sensory and motor systems, consider what basic functions they need to accomplish, and examine what neural circuits are involved. Next we explore whether the circuit motifs encountered are also found in central brain areas, with an emphasis on sensory-motor integration and learning. Finally we discuss design principles for neural circuits and what constraints have shaped their structure and function in the course of evolution. Given in alternate years; not offered 2015–16.

Bi/NB/BE 155. Neuropharmacology. *6 units (3-0-3); second term. Prerequisites: Bi/CNS/NB 150.* The neuroscience of drugs for therapy, for prevention, and for recreation. Students learn the prospects for new generations of medications in neurology, psychiatry, aging, and treatment of substance abuse. Topics: Types of drug molecules. Drug receptors. Electrophysiology. Drugs activate ion channels. Drugs block ion channels. Drugs activate and block G protein pathways. Drugs block neurotransmitter transporters. Pharmacokinetics. Recreational drugs. Nicotine Addiction. Opiate Addiction. Drugs for neurodegenerative diseases: Alzheimer's disease, Parkinson's disease. Drugs for epilepsy and migraine. Psychiatric diseases: nosology and drugs. The course is taught at the research level. Given in alternate years, not offered 2015–16.

Bi/NB 156. Molecular Basis of Behavior. *9 units (3-0-6); second term. Prerequisite: Bi/CNS/NB 150 or instructor's permission.* A lecture and discussion course on the neurobiology of behavior. Topics may include biological clocks, eating behavior, sexual behavior, addiction, mental illness, and neurodegenerative diseases. Given in alternate years; not offered 2015–16.

Bi/CNS/NB 157. Comparative Nervous Systems. *9 units (2-3-4); third term. Prerequisites: instructor's permission.* An introduction to the comparative study of the gross and microscopic structure of nervous systems. Emphasis on the vertebrate nervous system; also, the highly developed central nervous systems found in arthropods and cephalopods. Variation in nervous system structure with function and with behavioral and ecological specializations and the evolution of the vertebrate brain. Letter grades only. Given in alternate years; not offered 2015–16.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6); third term. Prerequisites: Bi 1, Bi 8, or instructor's permission.* An integrative approach to the study of vertebrate evolution combining comparative anatomical, behavioral, embryological, genetic, paleontological, and physiological findings. Special emphasis will be given to: (1) the modification of developmental programs in evolution; (2) homeostatic systems for temperature regulation; (3) changes in the life cycle governing longevity and death; (4) the evolution of brain and behavior. Letter grades only. Instructor: Allman. Given in alternate years; offered 2015–16.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3); third term. Prerequisites: Bi/CNS/NB 150 or instructor's permission.* A laboratory-based introduction to experimental methods used for electrophysiological studies of the central nervous system. Through the term, students investigate the physiological response properties of neurons in insect and mammalian brains, using extra- and intracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, electrode fabrication, stimulus presentation, and computer-based data analysis. Graded pass/fail. Instructor: Staff.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6); second term. Prerequisites: Bi/CNS/NB 150 or equivalent.* Offers a broad survey of methods and approaches to understanding in modern neurobiology. The focus is on understanding the tools of the discipline, and their use will be illustrated with current research results. Topics include: molecular genetics, disease models, transgenic and knock-in technology, virus tools, tracing methods, gene profiling, light and electron microscopy, optogenetics, optical and electrical recording, neural coding, quantitative behavior, modeling and theory. Instructor: Meister.

Bi 165. Microbiology Research: Practice and Proposal. *6 units (2-3-1); first term; Enrollment limited to instructor approval.* The course will serve to introduce graduate students to 1) ongoing research projects on campus involving the isolation, culture, and characterization of microbes and microbial communities; and 2) the process of writing fellowships having a microbiology focus to train students in preparing effective funding applications. The first phase will involve a series of research presentations by different laboratory groups over the course of three evenings for one week at the start of the course. The second phase over the term will involve training in grant writing by drafting an NSF-type proposal, and a final oral presentation of the students' proposals. Not offered 2015–16.

ESE/Bi 166. Microbial Physiology. *9 units (3-1-5).* For course description, see Environmental Science and Engineering.

ESE/Bi 168. Microbial Metabolic Diversity. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3- 0-6); first.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 173. Biophysical/Structural Methods. *9 units (3-0-6); second.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Molecular Machines in the Cell. *9 units (3-0-6); third.* For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/SS/Psy/NB 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6); second term.* Lectures and discussions on the underlying principles behind digital, video, differential interference contrast, phase contrast, confocal, and two-photon microscopy. The course will begin with basic geometric optics and characteristics of lenses and microscopes. Specific attention will be given to how different imaging elements such as filters, detectors, and objective lenses contribute to the final image. Course work will include critical evaluation of published images and design strategies for simple optical systems and the analysis and presentation of two- and three-dimensional images. The role of light microscopy in the history of science will be an underlying theme. No prior knowledge of microscopy will be assumed. Given in alternate years; not offered 2015–16.

Bi 181. Introduction to Computational Biology and Bioinformatics. *9 units (3-0-6); second term. Prerequisites: Bi 8, CS 2, or instructor's permission.* Biology is becoming an increasingly data-intensive science. Many of the data challenges in the biological sciences are distinct from other scientific disciplines because of the complexity involved. This course will introduce key computational, probabilistic, and statistical methods that are common in computational biology and bioinformatics. We will integrate these theoretical aspects to discuss solutions to common challenges that reoccur throughout bioinformatics including algorithms and heuristics for tackling DNA sequence alignments, phylogenetic reconstructions, evolutionary analysis, and population and human genetics. We will discuss these topics in conjunction with common applications including the analysis of high throughput DNA sequencing data sets and analysis of gene expression from RNA-Seq datasets. Instructor: Guttman.

Bi/BE 182. Animal Development and Genomic Regulatory Network Design. *9 units (3-0-6); second term. Prerequisites: Bi 8 and at least one of the following: Bi 111, Bi 114, or Bi 122 (or equivalents).* This course is focused on the genomic control circuitry of the encoded programs that direct developmental processes. The initial module of the course is devoted to general principles of development, with emphasis on transcriptional regulatory control and general properties of gene regulatory networks (GRNs). The second module provides mechanistic analyses of spatial control functions in multiple embryonic systems, and the third treats the explanatory and predictive power of the GRNs that control body plan development in mammalian, sea urchin, and Drosophila systems. Grades or pass/fail. Instructors: Stathopoulos, Peter, Davidson. Given in alternate years; offered 2015–16.

Bi/CNS/NB 184. The Primate Visual System. *9 units (3-1-5); third term.* This class focuses on the primate visual system, investigating it from an experimental, psychophysical, and computational perspective. The course will focus on two essential problems: 3-D vision and object recognition. Topics include parallel processing pathways, functional specialization, prosopagnosia, object detection and identification, invariance, stereopsis, surface perception, scene perception, navigation, visual memory, multidimensional readout, signal detection theory, oscillations, and synchrony. It will examine how a visual stimulus is represented starting in the retina, and ending in the frontal lobe, with a special emphasis placed on mechanisms for high-level vision in the parietal and temporal lobes. The course will include a lab component in which students design and analyze their own fMRI experiment. Given in alternate years; not offered 2015–16.

Bi/CNS/NB 185. Large Scale Brain Networks. *6 (2-0-4); third term.* This class will focus on understanding what is known about the large-scale organization of the brain, focusing on the mammalian brain. What large scale brain networks exist and what are their principles of function? How is information flexibly routed from one area to another? What is the function of thalamocortical loops? We will examine large scale networks revealed by anatomical tracing, functional connectivity studies, and mRNA expression analyses, and explore the brain circuits mediating complex behaviors such as attention, memory, sleep, multisensory integration, decision making, and object vision. While each of these topics could cover an entire course in itself, our focus will be on understanding the master plan--how the components of each of these systems are put together and function as a whole. A key question we will delve into, from both a biological and a theoretical perspective, is: how is information flexibly routed from one brain area to another? We will discuss the communication through coherence hypothesis, small world networks, and sparse coding. Instructor: Tsao. Given in alternate years, offered 2015–16.

CNS/Bi/EE/CS/NB 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi 188. Human Genetics and Genomics. *6 units (2-0-4); third term. Prerequisite: Bi 122; or graduate standing and instructor's permission.* Introduction to the genetics of humans. Subjects covered include human genome structure, genetic diseases and predispositions, the human genome project, forensic use of human genetic markers, human variability, and human evolution. Given in alternate years; not offered 2015–16.

Bi 189. The Cell Cycle. *6 units (2-0-4); third term. Prerequisites: Bi 8 and Bi 9.* The course covers the mechanisms by which eukaryotic cells control their duplication. Emphasis will be placed on the biochemical processes that ensure that cells undergo the key events of the cell cycle in a properly regulated manner. Not offered 2015–16.

Bi 190. Systems Genetics. *6 units (2-0-4); third term. Prerequisites: Bi 122.* Lectures covering how genetic and genomic analyses are used to understand biological systems. Emphasis is on genetic and genome-scale approaches used in model organisms such as yeast, flies, worms, and mice to elucidate the function of genes, genetic pathways and genetic networks. Instructor: Sternberg.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi 192. Introduction to Systems Biology. *6 units (2-0-4); first term. Prerequisites: Ma 1abc, and either Bi 8, CS1, or ACM 95 or instructor's permission.* The course will explore what it means to analyze biology from a systems-level point of view. Given what biological systems must do and the constraints they face, what general properties must biological systems have? Students will explore design principles in biology, including plasticity, exploratory behavior, weak-linkage, constrains that deconstrain, robustness, optimality, and evolvability. The class will read the equivalent of 2-3 scientific papers every week. The format will be a seminar with active discussion from all students. Students from multiple backgrounds are welcome: non-biology or biology students interested in learning systems-level questions in biology. Limited enrollment. Not offered 2015–16.

Bi/CNS/NB 195. Mathematics in Biology. *9 units (3-0-6); first term. Prerequisites: Multi-variable calculus.* This course develops the mathematical methods needed for a quantitative understanding of biological phenomena, including data analysis, formulation of simple models, and the framing of quantitative questions. Topics include: probability and stochastic processes, linear algebra and transforms, dynamical systems, scientific programming. Instructor: Meister. Given in alternate years; offered 2015–16.

Bi 199. Introduction to *MATLAB* for Biologists. *6 units (3-0-3); second term.* This hands-on course provides an introduction to *MATLAB*'s structure and syntax, writing of functions and scripts, image analysis, and data visualization. Instructor: Kennedy.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units; summer.* For course description, see Bioengineering.

Bi 204. Evolution of the Animal Body Plan. *6 units (2-0-4); third term. Prerequisite: Bi/BE 182 or equivalent. Qualified undergraduates are welcome.* Evolution of animal forms will be considered mechanistically in terms of change in the genomic regulatory programs underlying the developmental ontogeny of these forms, but within the framework provided by current concepts of animal phylogeny. Evolutionary mechanisms will be considered, as well, with respect to the real-time paleontological record and the changing conditions of Earth's environment through geological time. Principles emerging from the system biology of regulatory evolution will be emphasized. Given in alternate years; not offered 2015–16.

Bi 206. Biochemical and Genetic Methods in Biological Research. *6 units (2-0-4); third term. Prerequisite: graduate standing or instructor's permission.* This course will comprise in-depth discussions of selected methods in molecular biology and related fields. Given the enormous range of techniques available to a molecular biologist nowadays, the course will focus on a subset of these methods that includes recent and highly promising techniques, with an emphasis on their robustness and general applicability. Instructor: Varshavsky.

Bi 214. Hematopoiesis: A Developmental System. *6 units (2-0-4); third term. Prerequisite: Bi 114, or Bi/BE 182, or Bi 117 plus Bi/Ch 111, or graduate standing.* An advanced course with lectures and seminar presentations, based on reading from the current literature. The characteristics of blood cells offer unique insights into the molecular basis of lineage commitment and the mechanisms that control the production of diverse cell types from pluripotent precursors. The course will cover the nature of stem cells, the lineage relationships among differentiated cell types, the role of cytokines and cytokine receptors, apoptosis and lineage-specific proliferation, and how differentiation works at the level of gene regulation and regulatory networks. Roles of prominent regulatory molecules in hematopoietic development will be compared with their roles in other developmental systems. Emphasis will be on explanation of cellular and system-level phenomena in terms of molecular mechanisms. Given in alternate years; not offered 2015–16.

Bi/CNS/NB 216. Behavior of Mammals. *6 units (2-0-4); first term.* A course of lectures, readings, and discussions focused on the genetic, physiological, and ecological bases of behavior in mammals. A basic knowledge of neuroanatomy and neurophysiology is desirable. Instructor: Allman. Given in alternate years; offered 2015–16.

Bi/CNS/NB 217. Central Mechanisms in Perception. *6 units (2-0-4); first term.* Reading and discussions of behavioral and electrophysiological studies of the systems for the processing of sensory information in the brain. Given in alternate years; not offered 2015–16.

Bi/CNS/NB 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4); third term.* This advanced course will discuss the emerging science of neural "circuit breaking" through the application of molecular genetic tools. These include optogenetic and pharmacogenetic manipulations of neuronal activity, genetically based tracing of neuronal connectivity, and genetically based indicators of neuronal activity. Both viral and transgenic approaches will be covered, and examples will be drawn from both the invertebrate and vertebrate literature. Interested students who have little or no familiarity with molecular biology will be supplied with the necessary background information. Lectures and student presentations from the current literature. Instructor: Anderson.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4); second term. Prerequisites: Bi/BE 177 or a course in microscopy. Bi/BE 177 may be taken concurrently with this course.* Discussion and laboratory-based course covering the practical use of the confocal microscope, with special attention to the dynamic analysis of living cells and embryos. Course will begin with basic optics, microscope design, Koehler illumination, and the principles of confocal microscopy as well as other techniques for optical sectioning such as light sheet fluorescence microscopy (also called single plane illumination microscopy, SPIM). During the class students will construct a light sheet microscope based on the openSPIM design. Alongside the building of a light sheet microscope, the course will consist of semi-independent modules organized around different imaging challenges using confocal microscopes. Early modules will include a lab using lenses to build a cloaking device. Most of the early modules will focus on three-dimensional reconstruction of fixed cells and tissues. Later modules will include time-lapse confocal analysis of living cells and embryos. Students will also utilize the microscopes in the Beckman Institute Biological Imaging Facility to learn more advanced techniques such as spectral unmixing and fluorescence correlation spectroscopy. No prior experience with confocal microscopy will be assumed; however, a basic working knowledge of microscopes is highly recommended. Preference is given to graduate students who will be using confocal microscopy in their research. Instructor: Collazo. Given in alternate years; offered 2015–16.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. *9 units (3-2-4); third term. Prerequisites: Graduate standing or Bi/CNS/NB 150 or equivalent (e.g. Bi/CNS/NB 164).* The class covers the theoretical and practical aspects of using (1) optogenetic sensors and actuators to visualize and modulate the activity of neuronal ensembles; and (2) CLARITY approaches for anatomical mapping and phenotyping using tissue-hydrogel hybrids. Topics include: opsin design (including natural and artificial sources), delivery (genetic targeting, viral transduction), light activation requirements (power requirements, wavelength, fiberoptics, LEDs), compatible readout modalities (electrophysiology, imaging); design and use of methods for tissue clearing (tissue stabilization by polymers/hydrogels and selective extractions, such as of lipids for increased tissue transparency and macromolecule access). Class will discuss applications to neuronal circuits (case studies based on recent literature). The class offers hands-on lab exposure for opsin delivery, recording of light-modulated activity, and CLARITY tissue clearing, imaging, and 3D reconstruction of fluorescent samples. Instructor: Gradinaru.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4).* For course description, see Chemistry.

Ge/Bi 244. Paleobiology Seminar. *6 units (3-0-3).* For course description, see Geological and Planetary Sciences.

Ge/Bi/ESE 246. Molecular Geobiology Seminar. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

CNS/Bi/NB 247. Cerebral Cortex. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi 250 a. Topics in Molecular and Cellular Biology. *9 units (3-0-6); first term. Prerequisites: graduate standing.* Lectures and literature-based discussions covering research methods, scientific concepts and logic, research strategies and general principles of modern biology. Students will learn to critique papers in a wide range of fields, including molecular biology, developmental biology, genetics and neuroscience. Graded pass/fail. Instructor: Prober.

Bi 250 b. Topics in Systems Biology. *9 units (3-0-6); third term. Prerequisite: graduate standing.* The class will focus on quantitative studies of cellular and developmental systems in biology. It will examine the architecture of specific genetic circuits controlling microbial behaviors and multicellular development in model organisms. The course will approach most topics from both experimental and theoretical/computational perspectives. Specific topics include chemotaxis, multistability and differentiation, biological oscillations, stochastic effects in circuit operation, as well as higher-level circuit properties such as robustness. The course will also consider the organization of transcriptional and protein-protein interaction networks at the genomic scale. Instructors: Elowitz, Bois.

Bi/CNS/NB 250 c. Topics in Systems Neuroscience. *9 units (3-0-6); third term. Prerequisite: graduate standing.* The class focuses on quantitative studies of problems in systems neuroscience. Students will study classical work such as Hodgkin and Huxley's landmark papers on the ionic basis of the action potential, and will move from the study of interacting currents within neurons to the study of systems of interacting neurons. Topics will include lateral inhibition, mechanisms of motion tuning, local learning rules and their consequences for network structure and dynamics, oscillatory dynamics and synchronization across brain circuits, and formation and computational properties of topographic neural maps. The course will combine lectures and discussions, in which students and faculty will examine papers on systems neuroscience, usually combining experimental and theoretical/modeling components. Instructor: Siapas.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit. Prerequisite: graduate standing.* Presentations and discussion of research at Caltech in biology and chemistry. Discussions of responsible conduct of research are included. Instructors: Sternberg, Hay.

Bi 252. Responsible Conduct of Research. *4 units (2-0-2); third term.* This lecture and discussion course covers relevant aspects of the responsible conduct of biomedical and biological research. Topics include guidelines and regulations, ethical and moral issues, research misconduct, data management and analysis, research with animal or human subjects, publication, conflicts of interest, mentoring, and professional advancement. This course is required of all trainees supported on the NIH training grants in cellular and molecular biology and neuroscience, and is recommended for other graduate students in labs in the Division of Biology and Biological Engineering labs. Undergraduate students require advance instructor's permission. Graded pass/fail. Instructors: Meyerowitz, Sternberg, staff.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi/NB 256. Decision Making. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi 270. Special Topics in Biology. *Units to be arranged; first, second, third terms.* Students may register with permission of the responsible faculty member.

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged.* For course description, see Computation and Neural Systems.

Bi 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BUSINESS, ECONOMICS, AND MANAGEMENT

BEM 97. Undergraduate Research. *Units to be arranged; any term.Prerequisites: advanced BEM and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research on a business problem individually or in a small group. Graded pass/fail.

BEM 101. Selected Topics in Business Economics and Management. *Units to be determined by arrangement with the instructor; offered by announcement.* Topics to be determined by instructor. Instructors: Staff, visiting lecturers.

BEM 102. Introduction to Accounting. *9 units (3-0-6); first, second terms.* An introduction to accounting in business. Topics include financial accounting, cost accounting. Instructor: Wang.

BEM 103. Introduction to Finance. *9 units (3-0-6); first term. Prerequisites: Ec 11 required; one of the following: Ec 122, Ge/ESE 118, Ma 1/103, MA 112a, MA 112b.* An introduction to corporate finance. Economic theory is used to study asset valuation and financial decision making in business. Topics include financial decision making under certainty, introduction to valuation of risky assets (stocks and bonds), the corporate investment decision, dividend policy, and the corporate financing decision. Instructors: Roll.

BEM 104. Investments. *9 units (3-0-6); second term. Prerequisites: Ec 11, BEM 103, some familiarity with statistics.* Examines the theory of financial decision making and statistical techniques useful in analyzing financial data. Topics include portfolio selection, equilibrium security pricing, empirical analysis of equity securities, fixed-income markets, market efficiency, and risk management. Instructor: Gillen.

BEM 105. Options. *9 units (3-0-6); first term. Prerequisites: One of the following: Ec 122, Ge/ESE 118, Ma 1/103, MA 112a, MA 112b, or instructor's permission; BEM 103 strongly recommended; some familiarity with differential equations is helpful.* An introduction to option pricing theory and risk management in the discrete-time, binomial tree model, and the continuous-time Black-Scholes-Merton framework. Both the partial differential equations approach and the martingale approach (risk-neutral pricing by expected values) will be developed. The course will cover the basics of Stochastic, Ito Calculus. Instructors: Cvitanic.

BEM 106. Competitive Strategy. *9 units (3-0-6); second term. Prerequisite: Ec 11.* This course develops concepts appropriate for formulating strategy in a competitive environment, using a combination of case analysis and lectures. The course covers differentiation strategies, positioning to neutralize incumbency advantages, the product life cycle, organizational design as competitive strategy, signaling, cooperation strategies, pricing and price discrimination as competitive strategy, strategic use of option theory, and the war of attrition. Not offered 2015–16.

BEM 107. Applied Corporate Finance and Investment Banking. *9 units (3-0-6); third term. Prerequisites: BEM 103.* This course builds on the concepts introduced in BEM 103 and applies them to current issues related to the financial management, regulation, and governance of both ongoing corporations and new start-up companies. The fundamental theme is valuation. The course discusses how valuation is affected by, among others, the role of directors, regulation of mergers and acquisitions, and management incentives. Instructors: Cornell.

BEM 109. Fixed-Income and Credit-Risk Derivatives. *9 units (3-0-6); second term. Prerequisites: BEM 105.* An introduction to the models of interest rates, credit/default risk, and risk management. The focus is on continuous time models used in the practice of Financial Engineering for pricing and hedging fixed income securities. Two main models for credit risk are considered: structural and reduced form/intensity models. Instructors: Cvitanic.

BEM 110. Venture Capital. *9 units (3-0-6); second term. Prerequisites: BEM 102, 103.* An introduction to the theory and practice of venture capital financing of start-ups. This course covers the underlying economic principles and theoretical models relevant to the venture investment process, as well as the standard practices used by industry and detailed examples. Topics include: The history of VC; VC stages of financing; financial returns to private equity; LBOs and MBOs; people versus ideas; biotech; IPOs; and CEO transitions. Instructors: Ewens.

BEM 111. Quantitative Risk Management. *9 units (3-0-6); third term. Prerequisites: GE/ACM 118, BEM 105, or Ma 112.* An introduction to financial risk management. Concepts of Knightian risk and uncertainty; coherent risk; and commonly used metrics for risk. Techniques for estimating equity risk; volatility; correlation; interest rate risk; and credit risk are described. Discussions of fat-tailed (leptokurtic) risk, scenario analysis, and regime-switching methods provide an introduction to methods for dealing with risk in extreme environments. Instructor: Winston.

BEM 113. Financial Markets Laboratory. *9 units (3-3-3); second term. Prerequisite: BEM 103.* Financial economics is rather abstract and mathematical, and its value is difficult to ascertain from merely observing real-world financial markets, which operate in a complex environment where many key variables either remain unobserved or cannot be measured reliably. In this class, students will learn about the theories of asset pricing, options, investments performance evaluation, corporate finance, and banking/insurance through participation in a series of online market games. Grading will be based on a mixture of trading performance, written and oral reports. Not offered 2015–16.

BEM 114. Behavioral Finance. *9 units (3-0-6); third term. Prerequisites: Students are recommended (but not required) to take BEM 103 to become familiar with some basic concepts in finance.* Much of modern financial economics works with models in which agents are fully rational, in that they maximize expected utility and use Bayes' law to update their beliefs. Behavioral finance is a large and active field that develops and studies models in which some agents are less than fully rational. Such models have two building blocks: limits to arbitrage, which makes it difficult for rational traders to undo the dislocations caused by less rational traders; and psychology, which provides guidance for the kinds of deviations from full rationality we might expect to see. We discuss these two topics and consider a number of applications: asset pricing; individual trading behavior; the origin of bubbles; and financial crises. Instructor: Jin.

BEM/Ec 118. Environmental Economics. *9 units (3-0-6); first term. Prerequisite: Ec 11 or equivalent.* This course provides a survey from the perspective of economics of public policy issues regarding the management of natural resources and the protection of environmental quality. The course covers both conceptual topics and recent and current applications. Included are principles of environmental and resource economics, management of nonrenewable and renewable resources, and environmental policy with the focus on air pollution problems, both local problems (smog) and global problems (climate change). Not offered 2015–16.

BEM/Ec 131. Market Design. *9 units (3-0-6); first term. Prerequisites: Ec 11 or equivalent.* In this course we will study the design of markets and other market-like processes to address resource allocation and information extraction problems. We will cover the basic principles underlying the design process, as well as the practical considerations that arise when designing markets. Some examples include auctions (for spectrum, Treasury bills, IPO's, greenhouse gas permits, electricity), markets (cap and trade systems for pollution abatement or fishery management, scheduling, prediction), and matching systems (for college admissions, housing allocations, kidney exchange). Instructors: Ledyard.

BEM/Ec 150. Business Analytics. *9 units (3-0-6); third term. Prerequisites: GE/ESE 118 or Ec 122, and knowledge of R.* This class teaches how to use very large, cross-media datasets to infer what variables influence choices and trends of economic and business interest. Topics include database management, cleaning and visualization of data, statistical and machine learning methods, natural language processing, social and conventional media, personal sensors and devices, sentiment analysis, and controlled collection of data (including experiments). Grades are based on hands-on data analysis homework assignments and detailed analysis of one dataset. Instructor: Camerer.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6). Prerequisites: PS/Ec 172.* The course covers issues of how firms are organized. Topics include the distribution of power and returns among shareholders, managers, and other stakeholders; the role of law, public policy, and financial markets in constraining or enabling firms to solve problems they face; the interaction between history, financial market structure, and the ownership of very large firms. Each student is expected to write two substantial papers–drafts will be read by instructor and revised by students. Not offered 2015–16.

BEM 190. Undergraduate Research Project. *Units to be arranged; any term. Prerequisites: BEM 103, 106, and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research on a business problem individually or in small groups. Graded pass/fail.

CHEMICAL ENGINEERING

Ch/ChE 9. Chemical Synthesis and Characterization for Chemical Engineering. *9 units (1-6-2).* For course description, see Chemistry.

ChE 10. Introduction to Chemical Engineering. *1 unit (1-0-0); second term.* A series of weekly seminars given by chemical engineering faculty or an outside speaker, on a topic of current research. Topics will be presented at an informal, introductory level. Graded pass/fail.

ChE 15. Introduction to Chemical Engineering Computation. *9; second term. (3-0-6). Prerequisites: Ma 2 and ChE 62.* Introduction to the solution of engineering problems through the use of the computer. Elementary programming in Matlab is taught, and applied to solving chemical engineering problems in data analysis, process simulation, and optimization. No previous knowledge of computer programming is assumed. Instructor: Flagan.

ChE 62. Separation Processes. *9 units (3-0-6); first term.* Equilibrium staged separations. Membrane separations. Absorption. Distillation. Liquid-liquid extraction. Introduction to mass transfer. Instructor: Seinfeld.

ChE 63 ab. Chemical Engineering Thermodynamics. *9 units (3-0-6); second, third terms.* A comprehensive treatment of classical thermodynamics with engineering and chemical applications and an introduction to statistical thermodynamics. First and second laws. Applications to closed and open systems. Equations of state. Thermochemical calculations. Properties of real fluids. Power generation and refrigeration cycles. Multicomponent systems, excess properties, fugacities, activity coefficients, and models of nonideal solutions. Chemical potential. Phase and chemical reaction equilibria. Instructors: Tirrell, Ismagilov.

ChE 80. Undergraduate Research. *Units by arrangement.* Research in chemical engineering offered as an elective in any term other than in the senior year. Graded pass/fail.

ChE 90 ab. Senior Thesis. *9 units (0-4-5); first, second, third terms.* A research project carried out under the direction of a chemical engineering faculty member. The project must contain a significant design component. Students must submit a proposal outlining the proposed project, and clearly identifying its design component to the faculty mentor for the thesis and the chemical engineering option representative, by the beginning of the first term of the thesis for review and approval. A grade will not be assigned prior to completion of the thesis, which normally takes two terms. A P grade will be given for the first term and then changed to the appropriate letter grade at the end of the course.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1).* For course description, see Chemistry.

ChE 101. Chemical Reaction Engineering. *9 units (3-0-6); second term. Prerequisites: ChE 62 and ChE 63 ab, or instructor's permission.* Elements of chemical kinetics and chemically reacting systems. Homogeneous and heterogeneous catalysis. Chemical reactor analysis. Instructor: Arnold.

ChE 103 abc. Transport Phenomena. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 ab or concurrent registration, or instructor's permission.* A rigorous development of the basic differential equations of conservation of momentum, energy, and mass in fluid systems. Solution of problems involving fluid flow, heat transfer, and mass transfer. Instructors: Kornfield, Shapiro, Davis.

ChE 105. Dynamics and Control of Chemical Systems. *9 units (3-0-6); third term. Prerequisites: ACM 95 ab or concurrent registration, or instructor's permission.* Analysis of linear dynamic systems. Feedback control. Stability of closed-loop control systems. Root locus, Frequency response, and Nyquist analysis. Feedforward, cascade, and multivariable control systems. Instructor: Seinfeld.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6); second term.* This course combines three parts. First, it will cover fundamental aspects of kinetics, mass-transport, and fluid physics that are relevant to microfluidic systems. Second, it will provide an understanding of how new technologies are invented and reduced to practice. Finally, students in the course will work together to design microfluidic systems that address challenges in Global Health, with an emphasis on students' inventive contributions and creativity. Students will be encouraged and helped, but not required, to develop their inventions further by working with OTT and entrepreneurial resources on campus. Participants in this course benefit from enrollment of students with diverse backgrounds and interests. For chemical engineers, suggested but not required courses are ChE 101 (Chemical Reaction Engineering) and ChE 103abc (Transport Phenomena). Students are encouraged to contact the instructor to discuss enrollment. Instructor: Ismagilov.

ChE 114. Solid State NMR Spectroscopy For Materials Chemistry. *9 units (3-3-3); second Term. Prerequisites: Ch 21abc or instructor's permission.* Principles and applications of solid state NMR spectroscopy will be addressed with focus on structure and dynamics characterization of organic and inorganic solids. Topics include basic principles of NMR phenomena in solid state, high resolution techniques such as magic angle spinning (MAS), cross-polarization (CP) MAS, Double Rotation (DOR) and multiple-quantum MAS (MQMAS) for half integer quadrupole nuclei, and multiple pulse experiments for dipolar decoupling and recoupling, which expect to cover NMR methods that are routinely employed in studies of organic and inorganic materials chemistry. Hands-on experience will be provided via laboratory course on solid NMR spectrometers. Not offered 2015–16.

ChE 115. Electronic Materials Processing. *9 units (3-0-6); third term. Prerequisites: ChE 63 ab, ChE 103 abc, ChE 101, or instructor's permission.* Introduction into the gas-phase processing techniques used in the fabrication of electronic materials and devices. Kinetic theory of gases. Surface chemistry and gas-surface interaction dynamics. Film deposition techniques: physical and chemical vapor deposition, atomic layer epitaxy, liquid-phase epitaxy, molecular beam epitaxy. Introduction into plasmas and their role in patterned etching and layer deposition. Charging damage during plasma processing. Determination of key parameters that control the ion energy and flux to the wafer surface. Not offered 2015–16.

ChE 118. Introduction to the Design of Chemical Systems. *9 units (3-0-6); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, ChE 126, or instructor's permission.* Short-term, open-ended projects that require students to design a chemical process or product. Each team generates and filters ideas, identifies use cases and objectives, evaluates and selects a design strategy, develops a project budget, schedules milestones and tasks, and writes a proposal with supporting documentation. Each project must meet specified requirements for societal impact, budget, duration, person hours, environmental impact, safety, and ethics. Instructor: Vicic.

ChE 120. Optimal Design of Chemical Systems. *9 units (1-6-2); third term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, ChE 126, or instructor's permission.* Short-term, open-ended projects that require students to design and build a chemical process or manufacture a chemical product. Each team selects a project after reviewing a collection of proposals. Students use chemical engineering principles to design, build, test, and optimize a system, component, or product that fulfills specified performance requirements, subject to constraints imposed by budget, schedule, logistics, environmental impact, safety, and ethics. Instructor: Vicic.

ChE 126. Chemical Engineering Laboratory. *9 units (1-6-2); first term. Prerequisites: ChE 63 ab, ChE 101, ChE 103, ChE 105, or instructor's permission.* Short-term projects that require students to work in teams to design systems or system components. Projects typically include unit operations and instruments for chemical detection. Each team must identify specific project requirements, including performance specifications, costs, and failure modes. Students use chemical engineering principles to design, implement, and optimize a system (or component) that fulfills these requirements, while addressing issues and constraints related to environmental impact, safety, and ethics. Students also learn professional ethics through the analysis of case studies. Instructors: Giapis, Vicic.

ChE 128. Chemical Engineering Design Laboratory. *9 units (1-6-2); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103, or instructor's permission.* Short-term, open-ended research projects targeting chemical processes in microreactors. Projects include synthesis of chemical products or materials, detection and destruction of environmental pollutants, and other gas phase conversions. Each student is required to construct and troubleshoot his/her own microreactor, then experimentally evaluate and optimize independently the research project using chemical engineering principles. Where possible, cost analysis of the optimized process is performed. Instructors: Giapis, Vicic.

ChE 130. Biomolecular Engineering Laboratory. *9 units (1-5-3); third term. Prerequisites: ChE 63 ab, ChE 101 (may be taken concurrently) or instructor's permission.* Design, construction, and characterization of engineered biological systems that will be implemented in bacteria, yeast, and cell-free systems. Research problems will fall into the general areas of biomolecular engineering and synthetic biology. Emphasis will be on projects that apply rational and evolutionary design strategies toward engineering biological systems that exhibit dynamic, logical, or programmed behaviors. Instructors: Tirrell, Vicic.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6).* For course description, see Chemistry.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6).* For course description, see Chemistry.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6); third term.* An introduction to the physics that govern polymer structure and dynamics in liquid and solid states, and to the physical basis of characterization methods used in polymer science. The course emphasizes the scaling aspects of the various physical properties. Topics include conformation of a single polymer chain under different solvent conditions; dilute and semi-dilute solutions; thermodynamics of polymer blends and block copolymers; rubber elasticity; polymer gels; linear viscoelasticity of polymer solutions and melts; glass transition and crystallization. Not offered 2015–16.

ChE 151 ab. Physical and Chemical Rate Processes. *12 units (3-0-9); first, second terms.* The foundations of heat, mass, and momentum transfer for single and multiphase fluids will be developed. Governing differential equations; laminar flow of incompressible fluids at low and high Reynolds numbers; forced and free convective heat and mass transfer, diffusion, and dispersion. Emphasis will be placed on physical understanding, scaling, and formulation and solution of boundary-value problems. Applied mathematical techniques will be developed and used throughout the course. Instructor: Brady.

ChE 152. Heterogeneous Kinetics and Reaction Engineering. *9 units (3-0-6); first term. Prerequisite: ChE 101 or instructor's permission.* Survey of heterogeneous reactions and reaction mechanisms on metal and oxide catalysts. Characterization of porous catalysts. Reaction, diffusion, and heat transfer in heterogeneous catalytic systems. Instructor: Davis.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6); third term.* Discussion of homogeneous and heterogeneous catalytic reactions, with emphasis on the relationships between the two areas and their role in energy problems. Topics include catalysis by metals, metal oxides, zeolites, and soluble metal complexes; utilization of hydrocarbon resources; and catalytic applications in alternative energy approaches. Not offered 2015–16.

ESE/ChE 158. Aerosol Physics and Chemistry. *9 units (3-0-6); second term; Open to graduate students and seniors with instructor's permission.* For description, see Environmental Science and Engineering.

ChE/BE 163. Introduction to Biomolecular Engineering. *12 units (3-0-9); first term. Prerequisites: Bi/Ch 110 or instructor's permission and CS 1 or equivalent.* The course introduces rational design and evolutionary methods for engineering functional protein and nucleic acid systems. Rational design topics include molecular modeling, positive and negative design paradigms, simulation and optimization of equilibrium and kinetic properties, design of catalysts, sensors, motors, and circuits. Evolutionary design topics include evolutionary mechanisms and tradeoffs, fitness landscapes, directed evolution of proteins, and metabolic pathways. Some assignments require programming (MATLAB or Python). Instructors: Arnold, Pierce.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6); second term. Prerequisite: Ch 21 abc or instructor's permission.* An introduction to the fundamentals and simple applications of statistical thermodynamics. Foundation of statistical mechanics; partition functions for various ensembles and their connection to thermodynamics; fluctuations; noninteracting quantum and classical gases; heat capacity of solids; adsorption; phase transitions and order parameters; linear response theory; structure of classical fluids; computer simulation methods. Instructors: Wang, Miller.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6); first term. Prerequisite: ChE 63 ab or instructor's permission.* An advanced course emphasizing the conceptual structure of modern thermodynamics and its applications. Review of the laws of thermodynamics; thermodynamic potentials and Legendre transform; equilibrium and stability conditions; metastability and phase separation kinetics; thermodynamics of single-component fluid and binary mixtures; models for solutions; phase and chemical equilibria; surface and interface thermodynamics; electrolytes and polymeric liquids. Instructor: Wang.

ChE 174. Special Topics in Transport Phenomena. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 and ChE 151 ab or instructor's permission. May be repeated for credit.* Advanced problems in heat, mass, and momentum transfer. Introduction to mechanics of complex fluids; physicochemical hydrodynamics; microstructured fluids; colloidal dispersions; microfluidics; selected topics in hydrodynamic stability theory; transport phenomena in materials processing. Other topics may be discussed depending on class needs and interests. Not offered 2015–16.

ChE/BE/MedE 188. Molecular Imaging. *9 units (3-0-6); second term. Prerequisites: Bi/Ch 110, ChE 101 and ACM 95 or equivalent.* This course will cover the basic principles of biological and medical imaging technologies including magnetic resonance, ultrasound, nuclear imaging, fluorescence, bioluminescence and photoacoustics, and the design of chemical and biological probes to obtain molecular information about living systems using these modalities. Topics will include nuclear spin behavior, sound wave propagation, radioactive decay, photon absorption and scattering, spatial encoding, image reconstruction, statistical analysis, and molecular contrast mechanisms. The design of molecular imaging agents for biomarker detection, cell tracking, and dynamic imaging of cellular signals will be analyzed in terms of detection limits, kinetics, and biological effects. Participants in the course will develop proposals for new molecular imaging agents for applications such as functional brain imaging, cancer diagnosis, and cell therapy. Instructor: Shapiro.

ChE 190. Special Problems in Chemical Engineering. *Up to 9 units by arrangement; any term. Prerequisites: Instructor's permission and adviser's approval must be obtained before registering.* Special courses of readings or laboratory instruction. The student should consult a member of the faculty and prepare a definite program of reading, computation, theory and/or experiment. The student must submit a summary of progress at midterm and, at the end of the quarter, a final assignment designed in consultation with the instructor. This course may be credited only once. Grading: either grades or pass/fail, as arranged with the instructor. Instructors: Staff.

ChE 280. Chemical Engineering Research. *Offered to Ph.D. candidates in chemical engineering.* Main lines of research now in progress are covered in detail in section two.

CHEMISTRY

Ch 1 ab. General Chemistry. *6 units (3-0-3) first term; 9 units (4-0-5) second term.* Lectures and recitations dealing with the principles of chemistry. First term: electronic structure of atoms, periodic properties, ionic substances, covalent bonding, Lewis representations of molecules and ions, shapes of molecules, Lewis acids and bases, Bronsted acids and bases, hybridization and resonance, bonding in solids. Second term: chemical equilibria, oxidation and reduction, thermodynamics, kinetics, introduction to organic chemistry and the chemistry of life. Graded pass/fail. Instructors: Lewis (a), Reisman, Miller (b).

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5); third term. Prerequisites: Ch 1 ab, Ph 1 ab, Ma 1 ab.* Energy production and transduction in biological, chemical, and nuclear reactions. Bioenergetics: energy sources and storage; components of biological energy flows: pumps, motors, and solar cells; circuitry of biological energy flows and biological energy transduction pathways. Chemistry of energy production and utilization: fossil fuel utilization and energy conversion pathways; artificial photosynthesis, solar cells, and solar energy conversion. Principles of nuclear energy production: nuclear energy decay processes, fission and fusion reactions, and reactor principles. Not offered on a pass/fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Not offered 2015–16.

Ch 3 a. Fundamental Techniques of Experimental Chemistry. *6 units (1-3-2); first, second, third terms.* Introduces the basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. Freshmen who have gained advanced placement into Ch 41 or Ch 21, or who are enrolled in Ch 10, are encouraged to take Ch 3 a in the fall term. Graded pass/fail. Instructor: Mendez.

Ch 3 x. Experimental Methods in Solar Energy Conversion. *6 units (1-3-2); first, second, third terms.* Introduces concepts and laboratory methods in chemistry and materials science centered on the theme of solar energy conversion and storage. Students will perform experiments involving optical spectroscopy, electrochemistry, laser spectroscopy, nanoparticle synthesis, photochemistry, and photoelectrochemistry, culminating in the construction and testing of dye-sensitized solar cells. Instructor: Mendez.

Ch 4 ab. Synthesis and Analysis of Organic and Inorganic Compounds. *9 units (1-6-2). Prerequisites: Ch 1 (or the equivalent) and Ch 3 a or Ch 3 x. Ch 4 a is a prerequisite for Ch 4 b. Previous or concurrent enrollment in Ch 41 is strongly recommended.* Introduction to methods of synthesis, separation, purification, and characterization used routinely in chemical research laboratories. Ch 4 a focuses on the synthesis and analysis of organic molecules; Ch 4 b focuses on the synthesis and analysis of inorganic and organometallic molecules. Ch 4 a, second term; Ch 4 b, third term. Instructor: Mendez.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. *Ch 5 a 12 units (1-9-2), second term; Ch 5 b 12 units (1-9-2), first term. Prerequisites: Ch 4 ab. Ch 102 strongly recommended for Ch 5 b.* Modern synthetic chemistry. Specific experiments may change from year to year. Experiments illustrating the multistep syntheses of natural products (Ch 5 a), coordination complexes, and organometallic complexes (Ch 5 b) will be included. Methodology will include advanced techniques of synthesis and instrumental characterization. Terms may be taken independently. Instructors: Grubbs (a), Agapie (b). Part b not offered 2015–16.

Ch 6 ab. Physical and Biophysical Chemistry Laboratory. *10 units (1-6-3); second, third terms. Prerequisites: Ch 1, Ch 4 ab, and Ch 21 or Ch 24 or equivalents (may be taken concurrently).* Introduction to modern physical methods in chemistry and biology. Techniques include laser spectroscopy, microwave spectroscopy, electron spin resonance, nuclear magnetic resonance, mass spectrometry, FT-IR, fluorescence, scanning probe microscopies, and UHV surface methods. The two terms can be taken in any order. Instructor: Weitekamp.

Ch 7. Advanced Experimental Methods in Bioorganic Chemistry. *9 units (1-6-2); second term. Prerequisites: Ch 41 abc, and Bi/Ch 110, Ch 4 ab. Enrollment by instructor's permission. Preference will be given to students who have taken Ch 5 a or Bi 10.* This advanced laboratory course will provide experience in powerful contemporary methods used in chemical biology, including polypeptide synthesis and the selective labeling and imaging of glycoproteins in cells. Experiments will address amino acid protecting group strategies, biopolymer assembly and isolation, and product characterization. A strong emphasis will be placed on understanding the chemical basis underlying the successful utilization of these procedures. In addition, experiments to demonstrate the application of commercially available enzymes for useful synthetic organic transformations will be illustrated. Instructors: Hsieh-Wilson.

Ch 8. Experimental Procedures of Synthetic Chemistry. *9 units (1-6-2); first term. Prerequisites: Ch 1 ab and Ch 3 a or Ch 3 x. Previous or concurrent enrollment in Ch 41 is strongly recommended.* Introduction to the synthesis of organic and organometallic compounds, and to methods of separation, purification, and spectroscopic characterization used in chemical research. Instructor: Mendez.

Ch/ChE 9. Chemical Synthesis and Characterization for Chemical Engineering. *9 units (1-6-2); third term. Prerequisites: Ch 1 ab and Ch 3 a or Ch 3 x. Previous or concurrent enrollment in Ch 41 is strongly recommended.* Instruction in synthesis, separation, purification, and physical and spectroscopic characterization procedures of model organic and inorganic materials, with emphasis on chemical reactions such as polymerization, catalysis, and light absorption and emission. Enrollment priority given to chemical engineering majors. Instructor: Mendez.

Ch 10 abc. Frontiers in Chemistry. *3 units (2-0-1) first, second terms; 8 units (1-6-1) third term; Open for credit to freshmen and sophomores. Prerequisites: Ch 10 c prerequisites are Ch 10 ab, Ch 3 a or Ch 3 x, and either Ch 1 ab, Ch 41 ab, or Ch 21 ab, and instructor's permission.* Ch 10 ab is a weekly seminar by a member of the chemistry department on a topic of current research; the topic will be presented at an informal, introductory level. The other weekly session will acquaint students with the laboratory techniques and instrumentation used on the research topics. Ch 10 c is a research-oriented laboratory course, which will be supervised by a chemistry faculty member. Weekly class meetings will provide a forum for participants to discuss their research projects. Graded pass/fail. Instructors: Dervan, Hoelz.

Ch 14. Chemical Equilibrium and Analysis. *6 units (2-0-4); third term.* A systematic treatment of ionic equilibria in solution. Topics covered include acid-base equilibria in aqueous and nonaqueous solutions, complex ion formation, chelation, oxidation-reduction reactions. Also, introductory treatment of separations, chromatography and mass spectrometry. Instructors: TBD, Shahgholi.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); first term. Prerequisites: Ch 1 ab, Ch 3 a or Ch 3 x, or instructor's permission.* Laboratory experiments are used to illustrate modern instrumental techniques that are currently employed in industrial and academic research. Emphasis is on determinations of chemical composition, measurement of equilibrium constants, evaluation of rates of chemical reactions, and trace-metal analysis. Instructors: Dalleska.

Ch 21 abc. Physical Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2; Ma 3 is recommended.* Atomic and molecular quantum mechanics, spectroscopy, thermodynamics, statistical mechanics, and chemical kinetics. Instructors: Okumura, Cai, Beauchamp.

Ch 24. Introduction to Biophysical Chemistry: Spectroscopy. *9 units (3-0-6); second term. Prerequisites: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2 and Ch 21 a.* Develops the basic principles of the interaction of light with matter, including spectroscopic and scattering methods of macromolecular structure determination, with emphasis on biochemical and biophysical applications. Instructor: Heath.

Ch 25. Introduction to Biophysical Chemistry: Thermodynamics. *9 units (3-0-6); third term. Prerequisites: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2; Ch 21 a and Ch 24 recommended.* Develops the basic principles of solution thermodynamics, transport processes, and reaction kinetics, with emphasis on biochemical and biophysical applications. Instructor: Rees.

Ch 41 abc. Organic Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 ab or instructor's permission.* The synthesis, structure, and mechanisms of reactions of organic compounds. Instructors: Dougherty (a), Hsieh-Wilson (b), Fu (c)

Ch 80. Chemical Research. *Offered to B.S. candidates in chemistry. Units in accordance with work accomplished. Prerequisite: consent of research supervisor.* Experimental and theoretical research requiring a report containing an appropriate description of the research work.

Ch 81. Independent Reading in Chemistry. *Units by arrangement. Prerequisite: instructor's permission.* Occasional advanced work involving reading assignments and a report on special topics. No more than 12 units in Ch 81 may be used as electives in the chemistry option.

Ch 82/182. Senior Thesis Research. *9 units; first, second, third terms. Prerequisites: instructor's permission.* Three terms of Ch 82/182 are to be completed during the junior and/or senior year of study. Ch 182 is taken only by students pursuing a joint B.S./M.S. degree in Chemistry. At the end of the third term, students enrolled in Ch 82 will present a thesis of approximately 20 pages (excluding figures and references) to the mentor and the Chemistry Curriculum and Undergraduate Studies Committee. The thesis must be approved by both the research mentor and the CUSC. Students enrolled in Ch 182 will present a Masters Thesis, as described in requirements for the Masters degree. An oral thesis defense will be arranged by the CUSC in the third term for all enrollees. The first two terms of Ch 82/182 will be taken on a pass/fail basis, and the third term will carry a letter grade. Instructor: Rees.

Ch 90. Oral Presentation. *3 units (2-0-1); second term.* Training in the techniques of oral presentation of chemical and biochemical topics. Practice in the effective organization and delivery of technical reports before groups. Strong oral presentation is an essential skill for successful job interviews and career advancement. Graded pass/fail. Instructors: Zewail, Bikle.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1); first, second terms.* Training in the writing of scientific research papers for chemists and chemical engineers. *Fulfills the Institute scientific writing requirement.* Instructor: TBD.

Ch 102. Introduction to Inorganic Chemistry. *9 units (3-0-6); third term. Prerequisites: Ch 41 ab.* Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, organometallic and biological inorganic chemistry Instructors: Agapie.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8).* For course description, see Biology.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8).* For course description, see Biology.

Ch 112. Inorganic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 102 or instructor's permission.* Introduction to group theory, ligand field theory, and bonding in coordination complexes and organo-transition metal compounds. Systematics of synthesis, bonding, and reactivities of commonly encountered classes of transition metal compounds. Instructor: Agapie.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8).* For course description, see Biology.

Ch 117. Introduction to Electrochemistry. *9 units (3-0-6); second term.* Discussion of the structure of electrode-electrolyte interface, the mechanism by which charge is transferred across it, and experimental techniques used to study electrode reactions. Topics change from year to year but usually include diffusion currents, polarography, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Not offered 2015–16.

Ch 120 ab. Nature of the Chemical Bond. *Ch 120 a: 9 units (3-0-6), first term; Ch 120 b: (1-1-7), second term. Prerequisite: general exposure to quantum mechanics (e.g., Ch 21 a).* Modern ideas of chemical bonding, with an emphasis on qualitative concepts useful for predictions of structures, energetics, excited states, and properties. Part a: The quantum mechanical basis for understanding bonding, structures, energetics, and properties of materials (polymers, ceramics, metals alloys, semiconductors, and surfaces), including transition metal and organometallic systems with a focus on chemical reactivity. The emphasis is on explaining chemical, mechanical, electrical, and thermal properties of materials in terms of atomistic concepts. Part b: The student does an individual research project using modern quantum chemistry computer programs to calculate wavefunctions, structures, and properties of real molecules. Instructor: Goddard.

Ch 121 ab. Atomic-Level Simulations of Materials and Molecules. *Ch 121 a: 9 units (3-0-6) second term; Ch 121 b (1-1-7) first term. Prerequisites: Ch 21 a or Ch 125 a.* Atomistic-based methods for predicting the structures and properties of molecules and solids and simulating the dynamical properties. The course will highlight theoretical foundations and applications of atomistic simulations to current problems in such areas as biological systems (proteins, DNA, carbohydrates, lipids); polymers (crystals, amorphous systems, copolymers); semiconductors (group IV, III-V, surfaces, defects); inorganic systems (ceramics, zeolites, superconductors, and metals); organometallics, and catalysis (heterogeneous and homogeneous). Part a covers the basic methods with hands-on applications to systems of interest using modern software. The homework for the 1st 5 weeks emphasizes computer-based solutions. For the exams and 2nd 5 weeks of the homework each student selects a short research project and uses atomistic simulations to solve it. For part b each student selects a more extensive research project and uses atomistic simulations to solve it. Instructor: Goddard.

Ch 122. Structure Determination by X-ray Crystallography. *9 units (3-0-6); first term. Prerequisites: Ch 21 abc or instructor's permission.* This course provides an introduction to small molecule X-ray crystallography. Topics include symmetry, space groups, diffraction by crystals, the direct and reciprocal lattice, Patterson and direct methods for phase determination, and structure refinement. It will cover both theoretical and applied concepts and include hands-on experience in data collection, structure solution and structure refinement. Instructor: Takase.

Ch 125abc. The Elements of Quantum Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ch 21 abc or an equivalent brief introduction to quantum mechanics.* A first course in molecular quantum mechanics consisting of a quantitative treatment of quantum mechanics with applications to systems of interest to chemists. The basic elements of quantum mechanics, the electronic structure of atoms and molecules, the interactions of radiation fields and matter, scattering theory, and reaction rate theory. Instructor: TBD

Ch 126. Molecular Spectra and Molecular Structure. *9 units (3-0-6); third term. Prerequisite: Ch 21 and Ch 125 a taken concurrently, or* *instructor's permission.* Quantum mechanical foundations of the spectroscopy of molecules. Topics include quantum theory of angular momentum, rovibrational Hamiltonian for polyatomic molecules, molecular symmetry and permutation-inversion groups, electronic spectroscopy, interaction of radiation and matter. Instructors: Giapis, Vicic.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); third term. Prerequisites: instructor's permission.* For course description, see Geological and Planetary Sciences.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6).* For course description, see Biology.

Ch 135. Chemical Dynamics. *9 units (3-0-6); second term. Prerequisites: Ch 21 abc and Ch 41 abc, or equivalent, or instructor's permission.* Introduction to the kinetics and dynamics of chemical reactions. Topics include scattering cross sections, rate constants, intermolecular potentials, classical two-body elastic scattering, reactive scattering, nonadiabatic processes, statistical theories of unimolecular reactions, photochemistry, laser and molecular beam methods, theory of electron transfer, solvent effects, condensed phase dynamics, surface reactions, isotope effects. Instructor: Okumura.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6); second, third terms. Prerequisite: APh/EE 9 ab or instructor's permission.* The properties and photoelectrochemistry of semiconductors and semiconductor/liquid junction solar cells will be discussed. Topics include optical and electronic properties of semiconductors; electronic properties of semiconductor junctions with metals, liquids, and other semiconductors, in the dark and under illumination, with emphasis on semiconductor/liquid junctions in aqueous and nonaqueous media. Problems currently facing semiconductor/liquid junctions and practical applications of these systems will be highlighted. Not offered 2015–16.

Ch 143. NMR Spectroscopy for Structural Identification. *9 units (3-0-6); third term. Prerequisites: Ch 41 abc.* This course will address both one-dimensional and two-dimensional techniques in NMR spectroscopy which are essential to elucidating structures of organic and organometallic samples. Dynamic NMR phenomena, multinuclear, paramagnetic and NOE effects will also be covered. An extensive survey of multipulse NMR methods will also contribute to a clear understanding of two-dimensional experiments. (Examples for Varian NMR instrumentation will be included.) Instructor: Virgil.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 41 abc; Ch 21 abc recommended.* An advanced survey of selected topics in modern physical organic chemistry. Topics vary from year to year and may include structural and theoretical organic chemistry; molecular recognition/supramolecular chemistry; reaction mechanisms and the tools to study them; reactive intermediates; materials chemistry; pericyclic reactions; and photochemistry. Instructor: Dougherty (a). Part b not offered 2015–16.

Ch 145. Bioorganic Chemistry of Proteins. *9 units (3-0-6); first term. Prerequisite: Ch 41 abc; Bi/Ch 110 recommended.* An advanced survey of current and classic topics in bioorganic chemistry/chemical biology. The content will vary from year to year and may include the structure, function, and synthesis of peptides and proteins; enzyme catalysis and inhibition; carbohydrates and glycobiology; chemical genetics; genomics and proteomics; posttranslational modifications; chemical tools to study cellular dynamics; and enzyme evolution. Not offered 2015–16.

Ch 146. Bioorganic Chemistry of Nucleic Acids. *9 units (3-0-6). Prerequisite: Ch 41 ab.* The course will examine the bioorganic chemistry of nucleic acids, including DNA and RNA structures, molecular recognition, and mechanistic analyses of covalent modification of nucleic acids. Topics include synthetic methods for the construction of DNA and RNA; separation techniques; recognition of duplex DNA by peptide analogs, proteins, and oligonucleotide-directed triple helical formation; RNA structure and RNA as catalysts (ribozymes). Not offered 2015–16.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6), second term. Prerequisite: Ch 41 abc.* An introduction to the chemistry of polymers, including synthetic methods, mechanisms and kinetics of macromolecule formation, and characterization techniques. Instructor: Grubbs. Course will be offered second term. Instructor: Grubbs.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 149. Tutorial in Organic Chemistry. *6 units (2-0-4); first term. Prerequisites: Ch 41 abc and instructor's permission.* Discussion of key principles in organic chemistry, with an emphasis on reaction mechanisms and problem-solving. This course is intended primarily for first-year graduate students with a strong foundation in organic chemistry. Meets during the month of October. Graded pass/fail. Instructors: Fu, Reisman.

Ch 153 ab. Advanced Inorganic Chemistry. *9 units (3-0-6); second, third terms. Prerequisites: Ch 112 and Ch 21 abc or concurrent registration.* Ch 153 a: Topics in modern inorganic chemistry. Electronic structure, spectroscopy, and photochemistry with emphasis on examples from the modern research literature. Ch 153 b: Applications of physical methods toward the characterization of inorganic and bioinorganic species. A range of spectroscopic approaches will be covered. Instructors: Gray, Winkler (a). Part b not offered 2015–16.

Ch 154 ab. Organometallic Chemistry. *9 units (3-0-6); second, third terms. Prerequisite: Ch 112 or equivalent.* A general discussion of the reaction mechanisms and the synthetic and catalytic uses of transition metal organometallic compounds. Second term: a survey of the elementary reactions and methods for investigating reaction mechanisms. Third term: contemporary topics in inorganic and organometallic synthesis, structure and bonding, and applications in catalysis. Instructor: Peters (a). Part b not offered 2015–16.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 166. Nonequilibrium Statistical Mechanics. *9 units (3-0-6); third term. Prerequisite: Ch 21 abc or equivalent.* Transport processes in dilute gases; Boltzmann equation; Brownian motion; Langevin and Fokker-Planck equations; linear response theory; time-correlation functions and applications; nonequilibrium thermodynamics. Instructor: Marcus.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3- 0-6); first.* For course description, see Biochemistry and Molecular Biophysics.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0).* For course description, see Environmental Science and Engineering.

BMB/Bi/Ch 173. Biophysical/Structural Methods. *9 units (3-0-6); second.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Molecular Machines in the Cell. *9 units (3-0-6); third.* For course description, see Biochemistry and Molecular Biophysics.

ESE/Ch 175. Physical Inorganic Chemistry of Natural Waters. *9 units (3-0-6); second term.* For course description, see Environmental Science and Engineering.

ESE/Ch 176. Physical Organic Chemistry of Natural Waters. *9 units (3-0-6); third term.* For course description, see Environmental Science and Engineering.

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. *9 units (3-0-6); first term.* For course description, see Biochemistry and Molecular Biophysics.

Ch 180. Chemical Research. *Units by arrangement. Offered to M.S. candidates in chemistry.* Graded pass/fail.

BMB/Ch 202 abc. Biochemistry Seminar Course. *1 unit; first, second, third terms.* For course description, see Biochemistry and Molecular Biophysics.

Ch 212. Bioinorganic Chemistry. *9 units (3-0-6); third term. Prerequisites: Ch 112 and Bi/Ch 110 or equivalent.* Current topics in bioinorganic chemistry will be discussed, including metal storage and regulation, metalloenzyme structure and reactions, biological electron transfer, metalloprotein design, and metal-nucleic acid interactions and reactions. Instructors: Gray, Winkler.

Ch 213 abc. Advanced Ligand Field Theory. *12 units (1-0-11); first, second, third terms. Prerequisite: Ch 21 abc or concurrent registration.* A tutorial course of problem solving in the more advanced aspects of ligand field theory. Recommended only for students interested in detailed theoretical work in the inorganic field. Instructors: Gray, staff.

Ch 224. Advanced Topics in Magnetic Resonance. *9 units (2-0-7); third term. Prerequisites: Ch 125 abc or Ph 125 abc or concurrent registration or equivalent; Ch 143.* A detailed presentation of some of the important concepts in magnetic resonance unified by the spin density operator formalism. Topics will include both classic phenomena and recent developments, especially in solid-state and two-dimensional NMR. Not offered 2015–16.

Ch 227 ab. Advanced Topics in Chemical Physics. *9 units (3-0-6); third term. Prerequisites: Ch 125 abc or Ph 125 abc or equivalent.* The goal of this course is to utilize approaches derived from the chemico-physical to understand what are often considered complex biological problems. The course is a literature driven course with a strong emphasis on student participation. Part b not offered 2015–16. Instructors: Heath (a).

Ch 228. Dynamics and Complexity in Physical and Life Sciences. *9 units (3-0-6); third term.* This course is concerned with the structure-dynamics-function of complex systems, from materials to chemical and biological functions. We will address principles of elementary dynamics as they relate to the nature of the structures involved. An overview of modern techniques, such as those involving lasers, NMR, diffraction and imaging will be overviewed. Applications include areas in physics, chemistry and biology, covering phenomena of interest, from coherence and chaos to molecular recognition and self-assembly. Course requirement, which includes writing a "science paper" and presentation, will be outlined in the first meeting. Instructors: Zewail.

BMB/Ch 230. Macromolecular Structure Determination with Modern X-ray Crystallography Methods. *12 units (2-4-6); Third term. For course description, see Biochemistry and Molecular Biophysics.*

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4); third term.* Transcriptional regulation in eukaryotes. Topics: the subunit structure of eukaryotic RNA polymerases and their role in transcriptional reactions; the composition of eukaryotic promoters, including regulatory units; general and specific transcription factors; developmental regulatory circuits and factors; structural motifs involved in DNA binding and transcriptional initiation and control. Instructors: Campbell, Parker.

Ch 242 ab. Chemical Synthesis. *9 units (3-0-6); first, second terms. Prerequisite: Ch 41 abc.* An integrated approach to synthetic problem solving featuring an extensive review of modern synthetic reactions with concurrent development of strategies for synthesis design. Part a will focus on the application of modern methods of stereocontrol in the construction of stereochemically complex acyclic systems. Part b will focus on strategies and reactions for the synthesis of cyclic systems. Instructor: Stoltz (a), Reisman (b).

Ch 247. Organic Reaction Mechanisms. *9 units (3-0-6); second term. Prerequisites: Ch 41 abc, Ch 242 a recommended.* This course will discuss and uncover useful strategies and tactics for approaching complex reaction mechanisms prevalent in organic reactions. Topics include: cycloaddition chemistry, rearrangements, radical reactions, metal-catalyzed processes, photochemical reactions among others. Recommended only for students interested in advanced study in organic chemistry or related fields. Not offered 2015–16.

Ch 250. Advanced Topics in Chemistry. *3 units; third term.* Content will vary from year to year; topics are chosen according to the interests of students and staff. Visiting faculty may present portions of this course. In Spring 2016 the class will be a seminar course in pharmaceutical chemistry with lectures by industrial researchers from both discovery (medicinal chemistry) and development (process chemistry) departments. Instructors: Fu, Grubbs, Stoltz.

Ch 280. Chemical Research. *Hours and units by arrangement.* By arrangement with members of the faculty, properly qualified graduate students are directed in research in chemistry.

CIVIL ENGINEERING

CE 90 abc. Structural Analysics and Design. *9 units (3-0-6); first, second, third terms. Prerequisite: ME 35 abc.* Structural loads; influence lines for statically determinate beams and trusses; deflection of beams; moment area and conjugate beam theorems; approximate methods of analysis of indeterminate structures; slope deflection and moment distribution techniques. Generalized stiffness and flexibility analyses of indeterminate structures. Design of selected structures in timber, steel, and reinforced concrete providing an introduction to working stress, load and resistance factor, and ultimate strength approaches. In each of the second and third terms a design project will be undertaken involving consideration of initial conception, cost-benefit, and optimization aspects of a constructed facility. Not offered 2015–16.

CE 100. Special Topics in Civil Engineering. *Units to be based upon work done, any term.* Special problems or courses arranged to meet the needs of first-year graduate students or qualified undergraduate students. Graded pass/fail.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aerospace.

CE/Ae/AM 108 ab. Computational Mechanics. *9 units (3-0-6); first, second terms. Prerequisite:Ae/AM/ME/CE 102 abc or Ae/GE/ME 160 ab, or instructor's permission.* Numerical methods and techniques for solving initial boundary value problems in continuum mechanics (from heat conduction to statics and dynamics of solids and structures). Finite difference methods, direct methods, variational methods, finite elements in small strains and at finite deformation for applications in structural mechanics and solid mechanics. Solution of the partial differential equations of heat transfer, solid and structural mechanics, and fluid mechanics. Transient and nonlinear problems. Computational aspects and development and use of finite element code. Not offered 2015–16.

CE/ME 112 ab. Hydraulic Engineering. *9 units (3-0-6); second, third terms. Prerequisites: ME 11 abc, ME 12 abc; ACM 95/100 or equivalent (may be taken concurrently).* A survey of topics in hydraulic engineering: open channel and pipe flow, subcritical/critical flow and the hydraulic jump, hydraulic structures (weirs, inlet and outlet works, dams), hydraulic machinery, hydrology, river and flood modeling, solute transport, sediment mechanics, groundwater flow. Instructor: Hall.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term.* For course description, see Applied Mechanics.

AM/CE 151 ab. Dynamics and Vibrations. *9 units (3-0-6).* For course description, see Applied Mechanics.

CE 160 ab. Structural and Earthquake Engineering. *9 units (3-0-6); second, third terms.* Matrix structural analysis of the static and dynamic response of structural systems, Newmark time integration, Newton-Raphson iteration methodology for the response of nonlinear systems, stability of iteration schemes, static and dynamic numerical analysis of planar beam structures (topics include the development of stiffness, mass, and damping matrices, material and geometric nonlinearity effects, formulation of a nonlinear 2-D beam element, uniform and nonuniform earthquake loading, soil-structure interaction, 3-D beam element formulation, shear deformations, and panel zone deformations in steel frames, and large deformation analysis), seismic design and analysis of steel moment frame and braced frame systems, steel member behavior (topics include bending, buckling, torsion, warping, and lateral torsional buckling, and the effects of residual stresses), reinforced concrete member behavior (topics include bending, shear, torsion, and PMM interaction), and seismic design requirements for reinforced concrete structures. Not offered 2015–16.

ME/CE 163. Mechanics and Rheology of Fluid-Infiltrated Porous Media. *9 units (3-0-6).* For course description, see Mechanical Engineering.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5).* For course description, see Aerospace.

CE/ME/Ge 173. Mechanics of Soils. *9 units (3-0-6); second term. Prerequisites: Continuum Mechanics - Ae/Ge/ME 160a.* Basic principles of stiffness, deformation, effective stress and strength of soils, including sands, clays and silts. Elements of soil behavior such as stress-strain-strength behavior of clays, effects of sample disturbance, anisotropy, and strain rate; strength and compression of granular soils; consolidation theory and settlement analysis; and critical state soil mechanics. Instructors: Asimaki.

ME/CE/Ge 174. Mechanics of Rocks. *9 units (3-0-6); third term.* For course description, see Mechanical Engineering.

CE 180. Experimental Methods in Earthquake Engineering. *9 units (1-5-3); first term. Prerequisite: AM/CE 151 abc or equivalent.* Laboratory work involving calibration and performance of basic transducers suitable for the measurement of strong earthquake ground motion, and of structural response to such motion. Study of principal methods of dynamic tests of structures, including generation of forces and measurement of structural response. Not offered 2015–16.

CE 181 ab. Engineering Seismology. *9 units (3-0-6); second, third terms.* Characteristics of potentially destructive earthquakes from the engineering point of view. Theory of seismometers, seismic waves in a continuum, plane waves in layered media, surface waves, basin waves, site effects, dynamic deformation of buildings, seismic sources, earthquake size scaling, earthquake hazard calculations, rupture dynamics. Instructor: Heaton.

CE 200. Advanced Work in Civil Engineering. *6 or more units as arranged; any term.* A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term.

CE 201. Advanced Topics in Civil Engineering. *9 units (3-0-6).* The faculty will prepare courses on advanced topics to meet the needs of graduate students.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/CE 221. Space Structures. *9 units (3-0-6).* For course description, see Aerospace.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. *6 units (2-0-4); third term.* A seminar-style course focusing on granular dynamics and instabilities as they relate to geophysical hazards such as fault mechanics, debris flows, and liquefaction. The course will consist of student-led presentations of active research at Caltech and discussions of recent literature. Not offered 2015–2016.

CE 300. Research in Civil Engineering. *Hours and units by arrangement.* Research in the field of civil engineering. By arrangements with members of the staff, properly qualified graduate students are directed in research.

COMPUTATION AND NEURAL SYSTEMS

CNS 100. Introduction to Computation and Neural Systems. *1 unit; first term.* This course is designed to introduce undergraduate and first-year CNS graduate students to the wide variety of research being undertaken by CNS faculty. Topics from all the CNS research labs are discussed and span the range from biology to engineering. Graded pass/fail. Instructor: Perona.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6); second, third terms. Prerequisites: Bi/CNS/NB 150 and CNS/Bi/Ph/CS/NB 187, or instructor's permission.* Introduction to the computations made by the brain during economic and social decision making and their neural substrates. First quarter: Signal detection theory. Unconscious and conscious processing. Emotion and the somatic marker hypothesis. Perceptual decision making. Reinforcement learning. Goal and habit learning. Facial processing in social neuroscience. Second quarter: Optimal Bayesian decision making and prospect theory. Standard and behavioral game theory. Evolution and group decision making. Collective decision making by animals. Exploration. Risk learning. Probabilistic sophistication. Instructors: Camerer, O'Doherty. Offered 2015–16.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5).* For course description, see Psychology.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5-0-3.5).* This course covers tools and statistical methods used in cognitive neuroscience research. Topics vary from year to year depending on the interests of the students. Recent topics include statistical modeling for fMRI data, experimental design for fMRI, and the preprocessing of fMRI data; part a offered spring term; bc not offered 2015–16.

Psy/CNS 130. Introduction to Human Memory. *9 units (3-0-6).* For course description, see Psychology.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6); second term.* This course will serve as an introduction to basic concepts, findings, and theory from the field of behavioral psychology, covering areas such as principles of classical conditioning, blocking and conditioned inhibition, models of classical conditioning, instrumental conditioning, reinforcement schedules, punishment and avoidance learning. The course will track the development of ideas from the beginnings of behavioral psychology in the early 20th century to contemporary learning theory. Not offered 2015–16.

EE/CNS/CS 148. Selected Topics in Computational Vision. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

Bi/CNS/NB 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

Bi/CNS/NB 153. Brain Circuits. *9 (3-0-6); Second Term. Prerequisites: Bi/CNS/NB 150 or equivalent.* For course description, see Biology.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. *12 units (3-3-6); second term.* For course description, see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

Bi/CNS/NB 157. Comparative Nervous Systems. *9 units (2-3-4); third term.* For course description, see Biology.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6); third term.* For course description, see Biology.

CS/CNS/EE 159. Advanced Topics in Machine Learning. *9 units (3-0-6); third term.* For course description, see Computer Science.

Bi/CNS/NB 162. *Cellular and Systems Neuroscience Laboratory. 12 units (2-7-3); third term. Prerequisites: Bi/CNS/NB 150 or instructor's permission.* For course description, see Biology.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6); second term. Prerequisites: Bi/CNS/NB 150 or equivalent.* For course description, see Biology.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3).* For course description, see Computer Science.

CNS/Bi/SS/Psy/NB 176. Cognition. *12 units (6-0-6); third term.* The cornerstone of current progress in understanding the mind, the brain, and the relationship between the two is the study of human and animal cognition. This course will provide an in-depth survey and analysis of behavioral observations, theoretical accounts, computational models, patient data, electrophysiological studies, and brain-imaging results on mental capacities such as attention, memory, emotion, object representation, language, and cognitive development. Not Offered 2015–16.

CNS 180. Research in Computation and Neural Systems. *Units by arrangement with faculty. Offered to precandidacy students.*

Bi/CNS/NB 184. The Primate Visual System. *9 units (3-1-5).* For course description, see Biology.

Bi/CNS/NB 185. Large Scale Brain Networks. *6 (2-0-4); third term.* For course description, see Biology.

CNS/Bi/EE/CS/NB 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4); second term.* Lecture, laboratory, and project course aimed at understanding visual information processing, in both machines and the mammalian visual system. The course will emphasize an interdisciplinary approach aimed at understanding vision at several levels: computational theory, algorithms, psychophysics, and hardware (i.e., neuroanatomy and neurophysiology of the mammalian visual system). The course will focus on early vision processes, in particular motion analysis, binocular stereo, brightness, color and texture analysis, visual attention and boundary detection. Students will be required to hand in approximately three homework assignments as well as complete one project integrating aspects of mathematical analysis, modeling, physiology, psychophysics, and engineering. Given in alternate years; offered 2015–16.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6); first term. Prerequisites: familiarity with digital circuits, probability theory, linear algebra, and differential equations. Programming will be required.* This course investigates computation by neurons. Of primary concern are models of neural computation and their neurological substrate, as well as the physics of collective computation. Thus, neurobiology is used as a motivating factor to introduce the relevant algorithms. Topics include rate-code neural networks, their differential equations, and equivalent circuits; stochastic models and their energy functions; associative memory; supervised and unsupervised learning; development; spike-based computing; single-cell computation; error and noise tolerance. Instructor: Perona.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi/CNS/NB 195. Mathematics in Biology. *9 (3-0-6).* For course description, see Biology.

Bi/CNS/NB 216. Behavior of Mammals. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS/NB 217. Central Mechanisms in Perception. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS/NB 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. *9 units (3-2-4); third term.* For course description, see Biology.

CNS/Bi/NB 247. Cerebral Cortex. *6 units (2-0-4); second term. Prerequisite: Bi/CNS/NB 150 or equivalent.* A general survey of the structure and function of the cerebral cortex. Topics include cortical anatomy, functional localization, and newer computational approaches to understanding cortical processing operations. Motor cortex, sensory cortex (visual, auditory, and somatosensory cortex), association cortex, and limbic cortex. Emphasis is on using animal models to understand human cortical function and includes correlations between animal studies and human neuropsychological and functional imaging literature. Instructor: Andersen. Given in alternate years. Not offered 2015–16.

Bi/CNS 250 c. Topics in Systems Neuroscience. *9 units (3-0-6).* For course description, see Biology.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (2-1-6); second term.* A course in functional brain imaging. An overview of contemporary brain imaging techniques, usefulness of brain imaging compared to other techniques available to the modern neuroscientist. Review of what is known about the physical and biological bases of the signals being measured. Design and implementation of a brain imaging experiment and analysis of data (with a particular emphasis on fMRI). Instructor: O'Doherty.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi/NB 256. Decision Making. *6 units (2-0-4); third term.* This special topics course will examine the neural mechanisms of reward, decision making, and reward-based learning. The course covers the anatomy and physiology of reward and action systems. Special emphasis will be placed on the representation of reward expectation; the interplay between reward, motivation, and attention; and the selection of actions. Links between concepts in economics and the neural mechanisms of decision making will be explored. Data from animal and human studies collected using behavioral, neurophysiological, and functional magnetic resonance techniques will be reviewed. Given in alternate years; offered 2015–16.

CNS 280. Research in Computation and Neural Systems. *Hours and units by arrangement. For graduate students admitted to candidacy in computation and neural systems.*

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0); first, second, third terms. For course description, see Social Sciences.*

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged. First, second, third terms.* Students may register with permission of the responsible faculty member.

COMPUTER SCIENCE

CS 1. Introduction to Computer Programming. *9 units (3-4-2); first term.* A course on computer programming emphasizing the program design process and pragmatic programming skills. It will use the Python programming language and will not assume previous programming experience. Material covered will include data types, variables, assignment, control structures, functions, scoping, compound data, string processing, modules, basic input/output (terminal and file), as well as more advanced topics such as recursion, exception handling and object-oriented programming. Program development and maintenance skills including debugging, testing, and documentation will also be taught. Assignments will include problems drawn from fields such as graphics, numerics, networking, and games. At the end of the course, students will be ready to learn other programming languages in courses such as CS 11, and will also be ready to take more in-depth courses such as CS 2 and CS 4. Instructor: Vanier.

CS 2. Introduction to Programming Methods. *9 units (2-6-1); second term. Prerequisites: CS 1 or equivalent.* CS 2 is a demanding course in programming languages and computer science. Topics covered include data structures, including lists, trees, and graphs; implementation and performance analysis of common algorithms; algorithm design principles, in particular recursion and dynamic programming; concurrency and network programming; basic numerical computation methods. Heavy emphasis is placed on the use of compiled languages and development tools, including source control and debugging. The course includes weekly laboratory exercises and written homework covering the lecture material and program design. The course is intended to establish a foundation for further work in many topics in the computer science option. Instructors: Barr, Desbrun.

CS 3. Introduction to Software Engineering. *9 units (2-4-3); third term. Prerequisites: CS 2 or equivalent.* CS 3 is a practical introduction to software engineering with an emphasis on understanding and minimizing risk in large software projects. Students will work in teams on a course-long project. Topics covered include revision control, code reviews, testing and testability, code readability, API design, refactoring, and documentation. The course provides opportunities to present your work to the class, and emphasizes working with other people's code, both that of classmates and pre-existing frameworks. Not offered 2015–16.

CS 4. Fundamentals of Computer Programming. *9 units (3-4-2); second term. Prerequisite: CS 1 or instructor's permission.* This course gives students the conceptual background necessary to construct and analyze programs, which includes specifying computations, understanding evaluation models, and using major programming language constructs (functions and procedures, conditionals, recursion and looping, scoping and environments, compound data, side effects, higher-order functions and functional programming, and object-oriented programming). It emphasizes key issues that arise in programming and in computation in general, including time and space complexity, choice of data representation, and abstraction management. This course is intended for students with some programming background who want a deeper understanding of the conceptual issues involved in computer programming. Instructor: Vanier.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6).* For course description, see Mathematics.

CS 9. Introduction to Computer Science Research. *1 unit (1-0-0); first term.* This course will introduce the research areas of the computer science faculty, through weekly overview talks by the faculty aimed at first-year undergraduates. Others may wish to take the course to gain an understanding of the scope of the field. Graded pass/fail. Instructor: Desbrun.

CS 11. Computer Language Shop. *3 units (0-3-0); first, second, third terms. Prerequisite: CS 1 or instructor's permission.* A self-paced lab that provides students with extra practice and supervision in transferring their programming skills to a particular programming language; the course can be used for any language of the student's choosing, subject to approval by the instructor. A series of exercises guide the student through the pragmatic use of the chosen language, building his or her familiarity, experience, and style. More advanced students may propose their own programming project as the target demonstration of their new language skills. CS 11 may be repeated for credit of up to a total of nine units. Instructors: Pinkston, Vanier.

CS 21. Decidability and Tractability. *9 units (3-0-6); second term. Prerequisite: CS 2 (may be taken concurrently).* This course introduces the formal foundations of computer science, the fundamental limits of computation, and the limits of efficient computation. Topics will include automata and Turing machines, decidability and undecidability, reductions between computational problems, and the theory of NP-completeness. Instructor: Umans.

CS 24. Introduction to Computing Systems. *9 units (3-3-3); third term. Prerequisites: Familiarity with C equivalent to having taken the CS 11 C track.* Basic introduction to computer systems, including hardware-software interface, computer architecture, and operating systems. Course emphasizes computer system abstractions and the hardware and software techniques necessary to support them, including virtualization (e.g., memory, processing, communication), dynamic resource management, and common-case optimization, isolation, and naming. Instructor: Pinkston.

CS 38. Introduction to Algorithms. *9 units (3-0-6); third term. Prerequisites: CS 2; Ma/CS 6 a or Ma 121 a; and CS 21 or CS/EE/Ma 129 a.* This course introduces techniques for the design and analysis of efficient algorithms. Major design techniques (the greedy approach, divide and conquer, dynamic programming, linear programming) will be introduced through a variety of algebraic, graph, and optimization problems. Methods for identifying intractability (via NP-completeness) will be discussed. Instructor: Schulman.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3).* For course description, see Electrical Engineering.

EE/CS 52 ab. Microprocessor Systems Laboratory. *9 units (3-6-0) second term; 6 units (1-5-0) third term; second, third terms.* For course description, see Electrical Engineering.

EE/CS 53. Microprocessor Project Laboratory. *12 units (0-12-0).* For course description, see Electrical Engineering.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) , 6 units (2-0-4), or 9 units (2-0-7) first term; 6 units (2-3-1), 9 units (2-6-1), or 12 units (2-9-1) second term; 12 units (2-9-1), 15 units (2-12-1), or 18 units (2-15-1), with instructor's permission, third term.* This course presents the fundamentals of modern multidisciplinary systems engineering in the context of a substantial design project. Students from a variety of disciplines will conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components. Specific tools will be provided for setting project goals and objectives, managing interfaces between component subsystems, working in design teams, and tracking progress against tasks. Students will be expected to apply knowledge from other courses at Caltech in designing and implementing specific subsystems. During the first two terms of the course, students will attend project meetings and learn some basic tools for project design, while taking courses in CS, EE, and ME that are related to the course project. During the third term, the entire team will build, document, and demonstrate the course design project, which will differ from year to year. Freshmen must receive permission from the lead instructor to enroll. Instructors: Blanquart, Murray.

CS 80 abc. Undergraduate Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained sufficiently early to allow time for planning the research.* Individual research project, carried out under the supervision of a member of the computer science faculty (or other faculty as approved by the computer science undergraduate option representative). Projects must include significant design effort. Written report required. Open only to upperclass students. Not offered on a pass/fail basis. Instructor: Staff.

CS 81 abc. Undergraduate Projects in Computer Science. *Units are assigned in accordance with work accomplished. Prerequisites: Consent of supervisor is required before registering.* Supervised research or development in computer science by undergraduates. The topic must be approved by the project supervisor, and a formal final report must be presented on completion of research. This course can (with approval) be used to satisfy the project requirement for the CS major. Graded pass/fail. Instructor: Staff.

CS 90. Undergraduate Reading in Computer Science. *Units are assigned in accordance with work accomplished. Prerequisites: Consent of supervisor is required before registering.* Supervised reading in computer science by undergraduates. The topic must be approved by the reading supervisor, and a formal final report must be presented on completion of the term. Graded pass/fail. Instructor: Staff.

CS 101 abc. Special Topics in Computer Science. *Units in accordance with work accomplished; offered by announcement. Prerequisites: CS 21 and CS 38, or instructor's permission.* The topics covered vary from year to year, depending on the students and staff. Primarily for undergraduates.

CS 102 abc. Seminar in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

CS 103 abc. Reading in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

ACM/CS 114. Parallel Algorithms for Scientific Applications. *9 units.* For course description, see Applied and Computational Mathematics.

CS 115. Functional Programming. *9 units (3-4-2); third term. Prerequisites: CS 1 and CS 4.* This course is a both a theoretical and practical introduction to functional programming, a paradigm which allows programmers to work at an extremely high level of abstraction while simultaneously avoiding large classes of bugs that plague more conventional imperative and object-oriented languages. The course will introduce and use the lazy functional language Haskell exclusively. Topics include: recursion, first-class functions, higher-order functions, algebraic data types, polymorphic types, function composition, point-free style, proving functions correct, lazy evaluation, pattern matching, lexical scoping, type classes, and modules. Some advanced topics such as monad transformers, parser combinators, dynamic typing, and existential types are also covered. Instructor: Vanier.

CS 116. Reasoning about Program Correctness. *9 units (3-0-6); first term. Prerequisite: CS 1 or equivalent.* This course presents the use of logic and formal reasoning to prove the correctness of sequential and concurrent programs. Topics in logic include propositional logic, basics of first-order logic, and the use of logic notations for specifying programs. The course presents a programming notation and its formal semantics, Hoare logic and its use in proving program correctness, predicate transformers and weakest preconditions, and fixed-point theory and its application to proofs of programs. Instructor: Staff.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6).* For course description, see Mathematics.

CS 118. Logic Model Checking for Formal Software Verification. *9 units (3-3-3); second term.* An introduction to the theory and practice of logic model checking as an aid in the formal proofs of correctness of concurrent programs and system designs. The specific focus is on automata-theoretic verification. The course includes a study of the theory underlying formal verification, the correctness of programs, and the use of software tools in designs. Not offered 2015–16.

CS 119. Reliable Software: Testing and Monitoring. *9 units (3-3-3); third term. Prerequisites: CS 1 or equivalent; CS 116 and CS 118* *are recommended.* The class discusses theoretical and practical aspects of software testing and monitoring. Topics include finite state machine testing algorithms, random testing, constraint-based testing, coverage measures, automated debugging, logics and algorithms for runtime monitoring, and aspect-oriented approaches to monitoring. Emphasis is placed on automation. Students will be expected to develop and use software testing and monitoring tools to develop reliable software systems. Not offered 2015–16.

CS 121. Introduction to Relational Databases. *9 units (3-0-6); first term. Prerequisites: CS 1 or equivalent.* Introduction to the basic theory and usage of relational database systems. It covers the relational data model, relational algebra, and the Structured Query Language (SQL). The course introduces the basics of database schema design and covers the entity-relationship model, functional dependency analysis, and normal forms. Additional topics include other query languages based on the relational calculi, data-warehousing and dimensional analysis, writing and using stored procedures, working with hierarchies and graphs within relational databases, and an overview of transaction processing and query evaluation. Extensive hands-on work with SQL databases. Instructor: Pinkston.

CS 122. Database System Implementation. *9 units (3-3-3); second term. Prerequisites: CS2, CS38, CS 121 and familiarity with Java, or instructor's permission.* This course explores the theory, algorithms, and approaches behind modern relational database systems. Topics include file storage formats, query planning and optimization, query evaluation, indexes, transaction processing, concurrency control, and recovery. Assignments consist of a series of programming projects extending a working relational database, giving hands-on experience with the topics covered in class. The course also has a strong focus on proper software engineering practices, including version control, testing, and documentation. Not offered 2015–16.

CS 123. Projects in Database Systems. *9 units (0-0-9); third term. Prerequisites: CS121 and CS122.* Students are expected to execute a substantial project in databases, write up a report describing their work, and make a presentation. Not offered 2015–16.

CS 124. Operating Systems. (*3-0-6); Second term. Prerequisites: CS 24.* This course explores the major themes and components of modern operating systems, such as kernel architectures, the process abstraction and process scheduling, system calls, concurrency within the OS, virtual memory management, and file systems. Students must work in groups to complete a series of challenging programming projects, implementing major components of an instructional operating system. Most programming is in C, although some IA32 assembly language programming is also necessary. Familiarity with the material in CS 24 is strongly advised before attempting this course. Instructor: Pinkston.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2.* For course description, see Electrical Engineering.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6), first and second terms; (1-4-4) third term. Prerequisite: basic knowledge of probability and discrete mathematics.* A basic course in information theory and computational complexity with emphasis on fundamental concepts and tools that equip the student for research and provide a foundation for pattern recognition and learning theory. *First term:* what information is and what computation is; entropy, source coding, Turing machines, uncomputability. *Second term:* topics in information and complexity; Kolmogorov complexity, channel coding, circuit complexity, NP-completeness. *Third term:* theoretical and experimental projects on current research topics. Not offered 2015–16.

ME/CS 132 ab. Advanced Robotics: Navigation and Vision. *9 units (3-6-0).* For course description, see Mechanical Engineering.

EE/CS/EST 135. Power System Analysis. *9 units (3-3-3); second term.* For course description, see Electrical Engineering.

CS 138. Computer Algorithms. *9 units (3-0-6); third term. Prerequisites: CS 21 and CS 38, or instructor's permission.* Design and analysis of algorithms. Techniques for problems concerning graphs, flows, number theory, string matching, data compression, geometry, linear algebra and coding theory. Optimization, including linear programming. Randomization. Basic complexity theory and cryptography. Instructor: Schulman.

CMS/CS 139. Analysis and Design of Algorithms. *12 units (3-0-9); second term.* For course description, see Computation and Mathematical Sciences.

CS 142. Distributed Computing. (*3-0-6); third term. Prerequisites: CS 24, CS 38.* Programming distributed systems. Mechanics for cooperation among concurrent agents. Programming sensor networks and cloud computing applications. Applications of machine learning and statistics by using parallel computers to aggregate and analyze data streams from sensors. Not offered 2015–16.

CS/EE 143. Communication Networks. *9 units (3-3-3); first term. Prerequisites: Ma 2, Ma 3, CS 24 and CS 38, or instructor permission.* This course introduces the basic mechanisms and protocols in communication networks, and mathematical models for their analysis. It covers topics such as digitization, switching, switch design, routing, error control (ARQ), congestion control, layering, queuing models, optimization models, basics of protocols in the Internet, wireless networks, and optical networks. Instructor: Low.

CMS/CS/EE 144. Networks: Structure Economics. *12 units (3-3-6); second term.* For course description, see Computing and Mathematical Sciences.

CS/EE 145. Projects in Networking. *9 units (0-0-9); third term. Prerequisites: Either CMS/CS/EE 144 or CS 141 b in the preceding term, or instructor permission.* Students are expected to execute a substantial project in networking, write up a report describing their work, and make a presentation. Instructor: Wierman.

CS/EE 146. Advanced Networking. *9 units (3-3-3); third term. Prerequisites: CS/EE 143 or instructor's permission.* This is a research-oriented course meant for undergraduates and beginning graduate students who want to learn about current research topics in networks such as the Internet, power networks, social networks, etc. The topics covered in the course will vary, but will be pulled from current research topics in the design, analysis, control, and optimization of networks, protocols, and Internet applications. Usually offered in alternate years. Not offered 2015–16.

EE/CNS/CS 148. Selected Topics in Computational Vision. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

SS/CS 149. Introduction to Algorithmic Economics. *9 units (3-0-6). Prerequisites: Ma 3, CS 24 and CS 38, or instructor permission.* For course description, see Social Science.

CS 150. Probability and Algorithms. *9 units (3-0-6); second term. Prerequisites: CS 38 a and Ma 5 abc.* Elementary randomized algorithms and algebraic bounds in communication, hashing, and identity testing. Game tree evaluation. Topics may include randomized parallel computation; independence, k-wise independence and derandomization; rapidly mixing Markov chains; expander graphs and their applications; clustering algorithms. Not offered 2015–16.

CS 151. Complexity Theory. *12 units (3-0-9); third term. Prerequisites: CS 21 and CS 38, or instructor's permission.* This course describes a diverse array of complexity classes that are used to classify problems according to the computational resources (such as time, space, randomness, or parallelism) required for their solution. The course examines problems whose fundamental nature is exposed by this framework, the known relationships between complexity classes, and the numerous open problems in the area. Not offered 2015–16.

CS/SS 152. Introduction to Data Privacy. *9 units (3-0-6); first term. Prerequisites: Ma 3, CS 24 and CS 38, or instructor's permission.* How should we define privacy? What are the tradeoffs between useful computation on large datasets and the privacy of those from whom the data is derived? This course will take a mathematically rigorous approach to addressing these and other questions at the frontier of research in data privacy. We will draw connections with a wide variety of topics, including economics, statistics, information theory, game theory, probability, learning theory, geometry, and approximation algorithms. Not offered 2015–16.

CS 153. Current Topics in Theoretical Computer Science. *9 units (3-0-6); second term. Prerequisites: CS 21 and CS 38, or instructor's permission.* May be repeated for credit, with permission of the instructor. Students in this course will study an area of current interest in theoretical computer science. The lectures will cover relevant background material at an advanced level and present results from selected recent papers within that year's chosen theme. Students will be expected to read and present a research paper. Instructor: Umans.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. *12 units (3-3-6); second term.* For course description see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6); first, third terms. Prerequisites: Ma 2 and CS 2, or equivalent.* Introduction to the theory, algorithms, and applications of automated learning. How much information is needed to learn a task, how much computation is involved, and how it can be accomplished. Special emphasis will be given to unifying the different approaches to the subject coming from statistics, function approximation, optimization, pattern recognition, and neural networks. Not offered 2015–16.

CS/CNS/EE 159. Advanced Topics in Machine Learning. *9 units (3-0-6); third term. Prerequisites: CS 155; strong background in statistics, probability theory, algorithms, and linear algebra; background in optimization is a plus as well.* This course focuses on current topics in machine learning research. This is a paper reading course, and students are expected to understand material directly from research articles. Students are also expected to present in class, and to do a final project. Instructors: Yue.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3); first term. Prerequisites: Ma 2 and extensive programming experience.* This course introduces the basic ideas behind computer graphics and its fundamental algorithms. Topics include graphics input and output, the graphics pipeline, sampling and image manipulation, three-dimensional transformations and interactive modeling, basics of physically based modeling and animation, simple shading models and their hardware implementation, and fundamental algorithms of scientific visualization. Students will be required to perform significant implementations. Instructor: Barr.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3); third term. Prerequisites: Ma 2 and CS/CNS 171 or instructor's permission.* This laboratory class offers students an opportunity for independent work covering recent computer graphics research. In coordination with the instructor, students select a computer graphics modeling, rendering, interaction, or related algorithm and implement it. Students are required to present their work in class and discuss the results of their implementation and any possible improvements to the basic methods. May be repeated for credit with instructor's permission. Instructor: Barr.

CS 176. Introduction to Computer Graphics Research. *9 units (3-3-3); second term. Prerequisite: CS/CNS 171, or 173, or 174.* The course will go over recent research results in computer graphics, covering subjects from mesh processing (acquisition, compression, smoothing, parameterization, adaptive meshing), simulation for purposes of animation, rendering (both photo- and nonphotorealistic), geometric modeling primitives (image based, point based), and motion capture and editing. Other subjects may be treated as they appear in the recent literature. The goal of the course is to bring students up to the frontiers of computer graphics research and prepare them for their own research. Instructor: Desbrun.

CS 177. Discrete Differential Geometry: Theory and Applications. *9 units (3-3-3); first term.* Topics include, but are not limited to, discrete exterior calculus; Whitney forms; DeRham and Whitney complexes; Morse theory; computational and algebraic topology; discrete simulation of thin shells, fluids, electromagnetism, elasticity; surface parameterization; Hodge decomposition. Not offered 2015–16.

CS 179. GPU Programming. *9 units (3-3-3); third term. Prerequisites: Working knowledge of C. Some experience with computer graphics algorithms preferred, but not required.* The use of Graphics Processing Units for computer graphics rendering is well known, but their power for general parallel computation is only recently being explored. Parallel algorithms running on GPUs can often achieve up to 100x speedup over similar CPU algorithms. This course covers programming techniques for the Graphics processing unit, focusing on visualization and simulation of various systems. Labs will cover specific applications in graphics, mechanics, and signal processing. The course will introduce the OpenGL Shader Language (GLSL) and nVidia's parallel computing architecture, CUDA. Labwork will require extensive programming. Instructor: Barr, Desbrun.

CS 180. Master's Thesis Research. *Units (total of 45) are determined in accordance with work accomplished.*

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3); first, second terms.* Digital integrated system design, with projects involving the design, verification, and testing of high-complexity CMOS microcircuits. First-term lecture and homework topics emphasize disciplined design, and include CMOS logic, layout, and timing; computer-aided design and analysis tools; and electrical and performance considerations. Each student is required in the first term to complete individually the design, layout, and verification of a moderately complex integrated circuit. Advanced topics second and third terms include self-timed design, computer architecture, and other topics that vary year by year. Projects are large-scale designs done by teams. Not offered 2015–16.

CNS/Bi/EE/CS/NB 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. *12 units (3-6-3) second term; (2-8-2) third term.* For course description, see Bioengineering.

ACM/CS/EE 218. Statistical Inference. *9 units (3-0-6); third term.* For course description, see Applied and Computational Mathematics.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

SS/CS 241. Topics in Algorithmic Economics. *9 units (3-0-6).* For course description, see Social Science.

CS 274 abc. Topics in Computer Graphics. *9 units (3-3-3); first, second, third terms. Prerequisite: instructor's permission.* Each term will focus on some topic in computer graphics, such as geometric modeling, rendering, animation, human-computer interaction, or mathematical foundations. The topics will vary from year to year. May be repeated for credit with instructor's permission. Not offered 2015–16.

CS 280. Research in Computer Science. *Units in accordance with work accomplished. Approval of student's research adviser and option adviser must be obtained before registering.*

CS 282 abc. Reading in Computer Science. *6 units or more by arrangement; first, second, third terms. Instructor's permission required.*

CS 286 abc. Seminar in Computer Science. *3, 6, or 9 units, at the instructor's discretion. Instructor's permission required.*

COMPUTING AND MATHEMATICAL SCIENCES

CMS/ACM 104. Linear Algebra and Applied Operator Theory. *12 units (3-0-9); first term. Prerequisites: Undergraduate prerequistes: Ma 1 abc (analytic track), Ma 2, and ACM 95 ab; or instructor's permission.* This course introduces the theory and applications of linear algebra and linear analysis. Lectures and homework will require the ability to understand and produce mathematical proofs. Theoretical topics may include topology of metric spaces, structure of Banach and Hilbert spaces, examples of normed spaces, duality, structure of linear operators, spectral theory, functional calculus for linear operators, and calculus in Banach spaces. Applications will be drawn from signal processing, numerical analysis, optimization, approximation, differential equations, control, and other areas. Emphasis will be placed on geometry and convexity. Instructors: Tropp.

CMS/ACM 113. Mathematical Optimization. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 ab, ACM 11, or instructor's permission.* Corequisite: It is suggested that students take CMS/ACM 104 concurrently. This class studies mathematical optimization from the viewpoint of convexity. Topics covered include duality and representation of convex sets; linear and semidefinite programming; connections to discrete, network, and robust optimization; relaxation methods for intractable problems; as well as applications to problems arising in graphs and networks, information theory, control, signal processing, and other engineering disciplines. Instructors: Chandrasekaran.

CMS/ACM 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6); first term. Prerequisites: Ma 2, Ma 3 or instructor's permission.* Introduction to fundamental ideas and techniques of stochastic analysis and modeling. Random variables, expectation and conditional expectation, joint distributions, covariance, moment generating function, central limit theorem, weak and strong laws of large numbers, discrete time stochastic processes, stationarity, power spectral densities and the Wiener-Khinchine theorem, Gaussian processes, Poisson processes, Brownian motion. The course develops applications in selected areas such as signal processing (Wiener filter), information theory, genetics, queuing and waiting line theory, and finance. Instructors: Owhadi.

CMS/CS 139. Analysis and Design of Algorithms. *12 units (3-0-9); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6a, CS 21, CS 38/138, CMS/ACM/EE 116, or instructor's permission.* This course covers advanced topics in the design and analysis of algorithms. Topics are drawn from approximation algorithms, randomized algorithms, online algorithms, streaming algorithms, and other areas of current research interest in algorithms. Instructors: Vidick.

CMS/CS/EE 144. Networks: Structure Economics. *12 units (3-3-6); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6a, and CS 38, or instructor permission.* Social networks, the web, and the internet are essential parts of our lives and we all depend on them every day, but do you really know what makes them work?This course studies the "big" ideas behind our networked lives. Things like, what do networks actually look like (and why do they all look the same)? How do search engines work? Why do memes spread the way they do? How does web advertising work? For all these questions and more, the course will provide a mixture of both mathematical analysis and hands-on labs. The course assumes students are comfortable with graph theory, probability, and basic programming. Instructors: Wierman.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. *12 units (3-3-6); second term. Prerequisites: background in algorithms and statistics (CS/CNS/EE/NB 154 or CS/CNS/EE 156 a or instructor's permission).* This course will cover popular methods in machine learning and data mining, with an emphasis on developing a working understanding of how to apply these methods in practice. This course will also cover core foundational concepts underpinning and motivating modern machine learning and data mining approaches. This course will be research-oriented, and will cover recent research developments. Instructors: Yue.

ACM/CS/EE/CMS 218. Statistical Inference. *12 units (3-0-9); second term.* See course description in Applied and Computational Mathematics.

CMS 290 abc. Computing and Mathematical Sciences Colloquium. *1 unit; first, second, third terms.* Registration open to graduate students only. This course is a research seminar covering topics at the intersection of mathematics, computation, and their applications. Speakers are internationally recognized researchers from mathematics, applied mathematics, statistics, computer science, electrical engineering, control theory, and related disciplines. Attendance is required. Staff.

CMS 300. Research in Computing and Mathematical Sciences. *Hours and units by arrangement.* Research in the field of computing and mathematical science. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructors: Staff.

CONTROL AND DYNAMICAL SYSTEMS

CDS 90 abc. Senior Thesis in Control and Dynamical Systems. *9 units (0-0-9); first, second, third terms. Prerequisite: CDS 110, CDS 112 or CDS 140 (may be taken concurrently).* Research in control and dynamical systems, supervised by a Caltech faculty member. The topic selection is determined by the adviser and the student and is subject to approval by the CDS faculty. First and second terms: midterm progress report and oral presentation during finals week. Third term: completion of thesis and final presentation. Not offered on a pass/fail basis. Instructor: Murray.

CDS 101. Design and Analysis of Feedback Systems. *6 units (2-0-4); first term. Prerequisites: Ma 1 and Ma 2 or equivalents.* An introduction to feedback and control in physical, biological, engineering, and information sciences. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, modeling and model reduction, linear vs. nonlinear models, and local vs. global behavior. This course is taught concurrently with CDS 110, but is intended for students who are interested primarily in the concepts and tools of control theory and not the analytical techniques for design and synthesis of control systems. Instructor: Murray.

CDS 110. Introduction to Feedback Control Systems. *12 units (3-0-9); first term. Prerequisites: Ma 1abc and Ma 2/102 or equivalents.* An introduction to analysis and design of feedback control systems, including classical control theory in the time and frequency domain. Input/output modeling of dynamical systems using differential equations and transfer functions. Stability and performance of interconnected systems, including use of block diagrams, Bode plots, the Nyquist criterion, and Lyapunov functions. Design of feedback controllers in state space and frequency domain based on stability, performance and robustness specifications. Instructors: Murray.

CDS 112. Control System Design. *9 units (3-0-6); second term. Prerequisites: CDS 110.* Optimization-based design of control systems, including optimal control and receding horizon control. Robustness and uncertainty management in feedback systems through stochastic and deterministic methods. Introductory random processes, Kalman filtering, and norms of signals and systems. Instructor: Doyle.

CDS 140. Introduction to Dynamics. *9 units (3-0-6); second term. Prerequisites: Ma 2/102 or equivalent, CMS/ACM 104.* Basics topics in dynamics for continuous state systems in continuous and discrete time, using linear and nonlinear differential equations and maps. Topics include equilibria/invariant sets, stability, Lyapunov functions/invariants, attractors and periodic solutions. Introduction to structural stability, bifurcations and eigenvalue crossing conditions. Instructor: Murray.

CDS 190. Independent Work in Control and Dynamical Systems. *Units to be arranged; first, second, third terms; maximum two terms. Prerequisite: CDS 110 or CDS 140.* Research project in control and dynamical systems, supervised by a CDS faculty member.

CDS 212. Introduction to Modern Control. *9 units (3-0-6); second term. Prerequisites: Ma2/102, CMS/ACM 104, CDS 110.* Introduction to modern control systems with emphasis on the role of control in overall system analysis and design. Examples drawn from throughout engineering and science. Open versus closed loop control. State-space methods, time and frequency domain, stability and stabilization, realization theory. Time-varying and nonlinear models. Uncertainty and robustness. Instructor: Doyle.

CDS 213. Robust Control. *9 units (3-0-6); third term. Prerequisites: CDS 212.* Linear systems, realization theory, time and frequency response, norms and performance, stochastic noise models, robust stability and performance, linear fractional transformations, structured uncertainty, optimal control, model reduction, m analysis and synthesis, real parametric uncertainty, Kharitonov's theorem, uncertainty modeling. Not offered 2015–16.

CDS 240. Nonlinear Dynamical Systems. *9 units (3-0-6); third term. Prerequisites: CDS 140.* Analysis of nonlinear dynamical systems modeled using differential equations, including invariant and center manifolds, bifurcations, limit cycles, regular and singular perturbations, the method of averaging, input/output stability. Additional advanced topics may be included based on student and instructor interests. Instructors: Doyle, Murray.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. *9 units; (3-0-6 a, 1-3-5- b).* For course description, see Aerospace.

CDS 270. Advanced Topics in Systems and Control. *Hours and units by arrangement.* Topics dependent on class interests and instructor. May be repeated for credit.

CDS 300 abc. Research in Control and Dynamical Systems. *Hours and units by arrangement.* Research in the field of control and dynamical systems. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructor: Staff.

ECONOMICS

Ec 11. Introduction to Economics. *9 units (3-2-4); first, second terms.* An introduction to economic methodology, models, and institutions. Includes both basic microeconomics and an introduction to modern approaches to macroeconomic issues. Students are required to participate in economics experiments. Instructors: Plott, Rangel.

Ec 97. Undergraduate Research. *Units to be arranged; any term. Prerequisites:Advanced economics and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research in Economics individually or in a small group. Graded pass/fail.

Ec 98 abc. Senior Research and Thesis. *Prerequisite: instructor's permission.* Senior economics majors wishing to undertake research may elect a variable number of units, not to exceed 12 in any one term, for such work under the direction of a member of the economics faculty.

Ec 101. Selected Topics in Economics. *Units to be determined by arrangement with the instructor; offered by announcement.* Topics to be determined by instructor. Instructors: Staff, visiting lecturers.

Ec 105. Industrial Organization. *9 units (3-0-6); first term. Prerequisites: Ec 11 or equivalent.* A study of how technology affects issues of market structure and how market structure affects observable economic outcomes, such as prices, profits, advertising, and research and development expenditures. Emphasis will be on how the analytic tools developed in the course can be used to examine particular industries—especially those related to internet commerce—in detail. Each student is expected to write one substantial paper. Not offered 2015–16.

Ec 106. Topics in Applied Industrial Organization. *9 units (3-0-6); first term. Prerequisite: Ec 11; Ec 116 recommended.* Topics include simulation of mergers in oligopolistic industries, valuation of intellectual property, price setting and concentration in the pharmaceutical market, and statistical analysis of combined tobacco and asbestos exposure. A term paper will be required. Not offered 2015–16.

Ec/Psy 109. Frontiers in Behavioral Economics. *9 units (3-0-6), first term. Prerequisites: Ec 11.* Behavioral economics studies agents who are biologically limited in computational ability, willpower and pure self-interest. An important focus is how those limits interact with economic institutions and firm behavior. This reading-driven course will cover new papers that are interesting and draw attention to a topic of importance to economics. Readings will cover lab and field experiments, axiomatic models of behavioral phenomena, and welfare. Each weekly discussion will begin with a 10-minute overview, then an inspection of the paper's scientific machinery, judge whether its conclusions are justified, and speculate about the scope of its generalizability. It should help students as referees and as writers. Assignments are two 1000-word summary-critiques. Instructor: Camerer.

Ec 116. Contemporary Socioeconomic Problems. *9 units (3-0-6). Prerequisites: Ec 11 and PS 12 or equivalents.* An analytical investigation of the economic aspects of certain current social issues. Topics: the economics of education, medical-care systems, urban affairs, and the welfare system. Not offered 2015–16.

BEM/Ec 118. Environmental Economics. *9 units (3-0-6).* For course description, see Business Economics and Management.

BEM/Ec 131. Market Design. *9 units (3-0-6); first term.* For course description, see Business Economics and Management.

Ec 121 ab. Theory of Value. *9 units (3-0-6); first, second terms. Prerequisites: Ec 11 and Ma 2 (may be taken concurrently).* A study of consumer preference, the structure and conduct of markets, factor pricing, measures of economic efficiency, and the interdependence of markets in reaching a general equilibrium. Instructor: Saito, Border.

Ec 122. Econometrics. *9 units (3-0-6); first term. Prerequisites: Ma 3.* The application of statistical techniques to the analysis of economic data. Instructors: Sherman.

Ec 123. Macroeconomics. *9 units (3-0-6); third term. Prerequisite: Ec 11 and modest ability to program in Matlab or Mathematica.* The role of time and uncertainty in understanding the behavior of economic aggregates such as investment, employment, and price levels. Emphasis is on representative-agent recursive equilibrium models. Topics include practical dynamic programming; job search, matching, and unemployment; asset pricing; monetary and fiscal policy; and taxation and insurance. Not offered 2015–16.

Ec/SS 124. Identification Problems in the Social Sciences. *9 units (3-0-6); second term. Prerequisites: Ec 122.* Statistical inference in the social sciences is a difficult enterprise whereby we combine data and assumptions to draw conclusions about the world we live in. We then make decisions, for better or for worse, based on these conclusions. A simultaneously intoxicating and sobering thought! Strong assumptions about the data generating process can lead to strong but often less than credible (perhaps incredible?) conclusions about our world. Weaker assumptions can lead to weaker but more credible conclusions. This course explores the range of inferences that are possible when we entertain a range of assumptions about how data is generated. We explore these ideas in the context of a number of applications of interest to social scientists. Instructors: Sherman.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6); second term. Prerequisites: Ec 11.* An examination of certain analytical and quantitative tools and their application to American economic development. Each student is expected to write two substantial papers - drafts will be read by instructor and revised by students. Not offered 2015–16.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Twentieth Century. *9 units (3-0-6); third term. Prerequisites: Ec 11.* Employs the theoretical and quantitative techniques of economics to help explore and explain the development of the European cultural area between 1000 and 1980. Topics include the rise of commerce, the demographic transition, the Industrial Revolution, and changes in inequality, international trade, social spending, property rights, and capital markets. Each student is expected to write nine weekly essays and a term paper. Instructors: Hoffman.

Ec 135. Economics of Uncertainty and Information. *9 units (3-0-6); first term. Prerequisites: Ec 11, Ma 2b.* An analysis of the effects of uncertainty and information on economic decisions. Included among the topics are individual and group decision making under uncertainty, expected utility maximization, insurance, financial markets and speculation, product quality and advertisement, and the value of information. Instructor: Agranov.

Ec 140. Economic Progress. *9 units (3-0-6); second term. Prerequisites: Ec 11 and Ma 2; Ec 122 recommended.* This course examines the contemporary literature on economic growth and development from both a theoretical and historical/empirical perspective. Topics include a historical overview of economic progress and the lack thereof; simple capital accumulation models; equilibrium/planning models of accumulation; endogenous growth models; empirical tests of convergence; the measurement and role of technological advancement; and the role of trade, institutions, property rights, human capital, and culture. Not offered 2015–16

Ec 145. Public Finance. *9 units (3-0-6), first term. Prerequisite: Ec 11 or equivalent.* An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Instructor: Ledyard.

BEM/Ec 150. Business Analytics. *9 units (3-0-6); third term. Prerequisites: ACM 118 or Ec 122, and knowledge of R.* For course description, see Business Economics and Management.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3); first, second, third terms. Section a required for sections b and c.* An examination of recent work in laboratory testing in the social sciences with particular reference to work done in social psychology, economics, and political science. Students are required to design and conduct experiments. Instructor: Plott.

PS/Ec 172. Game Theory. *9 units (3-0-6).* For course description, see Political Science.

Ec 181. Convex Analysis and Economic Theory. *9 units (3-0-6); first term. Prerequisites: Ma 2 ab, Ec 121 a.* Introduction to the use of convex analysis in economic theory. Includes a rigorous discussion of separating hyperplane theorems, continuity and differentiability properties of convex and concave functions, support functions, subdifferentials, Fenchel conjugacy, saddle-point theory, theorem of the alternative, and linear programming. Emphasis is on the finite-dimensional case, but infinite-dimensional spaces will be discussed. Applications to the theory of cost and production functions, decision theory, and game theory. Instructor: Border.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec 190. Undergraduate Research. *Units to be arranged; any term. Prerequisite: advanced economics course and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research in economics. Graded pass/fail. Instructor: Staff.

ELECTRICAL ENGINEERING

EE 1. Introduction to Electrical Engineering Seminar. *1 unit; second term*. Required for EE undergraduates. Weekly seminar given by faculty in the department broadly describing different areas of electrical engineering: circuits and VLSI, communications, control, devices, images and vision, information theory, learning and pattern recognition, MEMS and micromachining, networks, electromagnetics and opto-electronics, RF and microwave circuits and antennas, robotics and signal processing, and specifically, research going on at Caltech. Instructor: Staff.

EE 5. Introduction to Embedded Systems. *6 units (2-3-1); third term.* This course is intended to give the student a basic understanding of the major hardware and software principles involved in the specification and design of embedded systems. Topics include basic digital logic, CPU and embedded system architecture, and embedded systems programming principles (events, user interfaces, and multitasking). The class is intended for students who wish to gain a basic understanding of embedded systems or for those who would like an introduction to the material before taking EE/CS 51/52. Graded pass/fail. Instructor: George.

EE/ME 7. Introduction to Mechatronics. *6 units (2-3-1); second term.* Mechatronics is the multi-disciplinary design of electro-mechanical systems. This course is intended to give the student a basic introduction to such systems. The course will focus on the implementations of sensor and actuator systems, the mechanical devices involved and the electrical circuits needed to interface with them. The class will consist of lectures and short labs where the student will be able to investigate the concepts discussed in lecture. Topics covered include motors, piezoelectric devices, light sensors, ultrasonic transducers, and navigational sensors such as accelerometers and gyroscopes. Graded pass/fail. Instructor: George.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2).* For course description, see Applied Physics.

EE 40. Introduction to Semiconductors Devices. *9 units (3-0-6); third term. Prerequisites: APh/EE 9 ab, Ma 2, Ph 2.* This course provides an introduction to semiconductors and semiconductor sensors. The fundamental physics of semiconductor electronics and devices will be emphasized, together with their applications. Overview of electronic properties of semiconductor that are significant to device operation for integrated circuits. Silicon device fabrication technology. Metal-semiconductor contacts, p-n junctions, bipolar transistors, photoconductors, diodes, transistors, CCDs, MOS/MOSFET/CMOS imagers, temperature sensors, magnetic sensors, thermoelectricity, piezoresistivity, piezoelectrics, etc. Instructors: Choo.

EE 44. Circuits and Systems. *12 units (4-0-8); first term. Prerequisites: Ph1 abc, should be taken concurrently with Ma 2 and Ph 2 a.* Fundamentals of circuits and network theory, circuit elements, linear circuits, terminals and port presentation, nodal and mesh analysis, time-domain analysis of circuits and systems, sinusoidal response, introductory frequency domain analysis, transfer functions, poles and zeros, time and transfer constants, network theorems, transformers. Instructors: Hajimiri.

EE 45. Electronics Laboratory. *12 units (3-3-6); second term. Prerequisites: EE 44.* Fundamentals of electronic circuits and systems. Lectures on diodes, transistors, small-signal analysis, frequency- domain analysis, application of Laplace transform, gain stages, differential signaling, operational amplifiers, introduction to radio and analog communication systems. Laboratory sessions on transient response, steady-state sinusoidal response and phasors, diodes, transistors, amplifiers. Instructor: Emami.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3); first term.* The principles and design of microprocessor-based computer systems. Lectures cover both hardware and software aspects of microprocessor system design such as interfacing to input and output devices, user interface design, real-time systems, and table-driven software. The homework emphasis is on software development, especially interfacing with hardware, in assembly language. Instructor: George.

EE/CS 52 ab. Microprocessor Systems Laboratory. *9 units (3-6-0) second term; 6 units (1-5-0) third term; second, third terms.* Prerequisites: EE/CS 51 or equivalent. The student will design, build, and program a specified microprocessor-based system. This structured laboratory is organized to familiarize the student with electronic circuit construction techniques, modern development facilities, and standard design techniques. The lectures cover topics in microprocessor system design such as display technologies, interfacing with analog systems, and programming microprocessors in high-level languages. Instructors: George.

EE/CS 53. Microprocessor Project Laboratory. *12 units (0-12-0); first, second, third terms. Prerequisites: EE/CS 52 ab or equivalent.* A project laboratory to permit the student to select, design, and build a microprocessor-based system. The student is expected to take a project from proposal through design and implementation (possibly including PCB fabrication) to final review and documentation. May be repeated for credit. Instructor: George.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or up to 18 units (2-15-1) third term.* For course description, see Computer Science.

EE 80 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained during the junior year to allow sufficient time for planning the research.* Individual research project, carried out under the supervision of a member of the electrical engineering or computer science faculty. Project must include significant design effort. Written report required. Open only to senior electrical engineering, computer science, or electrical and computer engineering majors. Not offered on a pass/fail basis. Instructor: Potter.

EE 90. Analog Electronics Project Laboratory. *9 units (1-8-0); third term. Prerequisites: EE 40 and EE 45.* A structured laboratory course that gives the student the opportunity to design and build a simple analog electronics project. The goal is to gain familiarity with circuit design and construction, component selection, CAD support, and debugging techniques. Instructor: Megdal.

EE 91 ab. Experimental Projects in Electronic Circuits. *Units by arrangement; first, second terms. 12 units minimum each term. Prerequisite: EE 45. Recommended: EE/CS 51 and 52, and EE 114 ab (may be taken concurrently). Open to seniors; others only with instructor's permission.* An opportunity to do advanced original projects in analog or digital electronics and electronic circuits. Selection of significant projects, the engineering approach, modern electronic techniques, demonstration and review of a finished product. DSP/microprocessor development support and analog/digital CAD facilities available. Text: literature references. Instructor: Megdal.

EE 99. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering will be arranged. For undergraduates; students should consult with their advisers. Graded pass/fail.

EE 105 abc. Electrical Engineering Seminar. *1 unit; first, second, third terms.* All candidates for the M.S. degree in electrical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Hajimiri.

EST/EE/ME 109. Energy Technology and Policy. *9 units (3-0-6); first term.* For course description, see Energy Science and Technology.

EE 111. Signal-Processing Systems and Transforms. *9 units (3-0-6); first term. Prerequisites: Ma 1.* An introduction to continuous and discrete time signals and systems with emphasis on digital signal processing systems. Study of the Fourier transform, Fourier series, z-transforms, and the fast Fourier transform as applied in electrical engineering. Sampling theorems for continuous to discrete-time conversion. Difference equations for digital signal processing systems, digital system realizations with block diagrams, analysis of transient and steady state responses, and connections to other areas in science and engineering. Instructors: Vaidyanathan.

EE 112. Introduction to Digital Signal Processing. *9 units (3-0-6); second term. Prerequisites: EE 111 or equivalent. Math 3 recommended.* Fundamentals of digital signal processing, digital filtering, recursive and non recursive filters, linear phase and minimum phase systems, digital filter structures, allpass filters and applications, quantization and stability analysis, round-off noise calculations, Nyquist and sub-Nyquist sampling, elements of multirate signal processing, reconstruction of sparsely sampled signals, statistical signal processing and sensor array signal processing, and applications in various areas. . Offered 2015–16. Instructor: Vaidyanathan.

EE 113. Feedback and Control Circuits. *9 units (3-3-3); third term. Prerequisites: EE 45 or equivalent.* This class studies the design and implementation of feedback and control circuits. The course begins with an introduction to basic feedback circuits, using both op amps and transistors. These circuits are used to study feedback principles, including circuit topologies, stability, and compensation. Following this, basic control techniques and circuits are studied, including PID (Proportional-Integrated-Derivative) control, digital control, and fuzzy control. There is a significant laboratory component to this course, in which the student will be expected to design, build, analyze, test, and measure the circuits and systems discussed in the lectures. Instructors: George.

EE/MedE 114 ab. Analog Circuit Design. *12 units (4-0-8); second, third terms. Prerequisites: EE 44 or equivalent.* Analysis and design of analog circuits at the transistor level. Emphasis on design-oriented analysis, quantitative performance measures, and practical circuit limitations. Circuit performance evaluated by hand calculations and computer simulations. Recommended for juniors, seniors, and graduate students. Topics include: review of physics of bipolar and MOS transistors, low-frequency behavior of single-stage and multistage amplifiers, current sources, active loads, differential amplifiers, operational amplifiers, high-frequency circuit analysis using time- and transfer constants, high-frequency response of amplifiers, feedback in electronic circuits, stability of feedback amplifiers, and noise in electronic circuits, and supply and temperature independent biasing. A number of the following topics will be covered each year: trans-linear circuits, switched capacitor circuits, data conversion circuits (A/D and D/A), continuous-time Gm.C filters, phase locked loops, oscillators, and modulators. Instructors: Hajimiri. Offered 2015–16.

EE/MedE 115. Micro-/Nano-scales Electro-Optics. *9 units (3-0-6); first term. Prerequisites: Introductory electromagnetic class and consent of the instructor.* The course will cover various electro-optical phenomena and devices in the micro-/nano-scales. We will discuss basic properties of light, imaging, aberrations, eyes, detectors, lasers, micro-optical components and systems, scalar diffraction theory, interference/interferometers, holography, dielectric/plasmonic waveguides, and various Raman techniques. Topics may vary. Not offered 2015–16.

Ph/APh/EE/BE 118 ab. Physics of Measurement. *9 units (3-0-6); first and second terms.* For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. *9 units (3-0-6); third terms.* For course description, see Physics.

EE 119 abc. Advanced Digital Systems Design. *9 units (3-3-3) first, second term; 9 units (1-8-0) third term; first, second, third terms. Prerequisite: EE/CS 52 ab or CS/EE 181 a or CS 24.* Advanced digital design as it applies to the design of systems using PLDs and ASICs (in particular, gate arrays and standard cells). The course covers both design and implementation details of various systems and logic device technologies. The emphasis is on the practical aspects of ASIC design, such as timing, testing, and fault grading. Topics include synchronous design, state machine design, ALU and CPU design, application-specific parallel computer design, design for testability, PALs, FPGAs, VHDL, standard cells, timing analysis, fault vectors, and fault grading. Students are expected to design and implement both systems discussed in the class as well as self-proposed systems using a variety of technologies and tools. Not offered 2015–16.

EE 120. Topics in Information Theory. *9 units (3-0-6); third term.* This class introduces information measures such as entropy, information divergence, mutual information, information density from a probabilistic point of view, and discusses the relations of those quantities to problems in data compression and transmission, statistical inference, language modeling, game theory and control. Topics include information projection, data processing inequalities, sufficient statistics, hypothesis testing, single-shot approach in information theory, large deviations. Prerequisites: undergraduate calculus and probability; desirable but not required: EE126a. Instructors: Kostina.

EE/MedE 124. Mixed-mode Integrated Circuits. *9 units (3-0-6); first term. Prerequisites: EE 45 a or equivalent.* Introduction to selected topics in mixed-signal circuits and systems in highly scaled CMOS technologies. Design challenges and limitations in current and future technologies will be discussed through topics such as clocking (PLLs and DLLs), clock distribution networks, sampling circuits, high-speed transceivers, timing recovery techniques, equalization, monitor circuits, power delivery, and converters (A/D and D/A). A design project is an integral part of the course. Instructors: Emami.

EE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0); second term. Prerequisite: basic knowledge of digital electronics.* Study of programmable logic devices (CPLDs and FPGAs). Detailed study of the VHDL language, with basic and advanced applications. Review and discussion of digital design principles for combinational-logic, combinationalarithmetic, sequential, and state-machine circuits. Detailed tutorials for synthesis and simulation tools using FPGAs and VHDL. Wide selection of complete, real-world fundamental advanced projects, including theory, design, simulation, and physical implementation. All designs are implemented using state-of-the-art development boards. Offered 2015–16. Instructor: Pedroni.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2.* Shannon's mathematical theory of communication, 1948-present. Entropy, relative entropy, and mutual information for discrete and continuous random variables. Shannon's source and channel coding theorems. Mathematical models for information sources and communication channels, including memoryless, first- order Markov, ergodic, and Gaussian. Calculation of capacity and rate-distortion functions. Kolmogorov complexity and universal source codes. Side information in source coding and communications. Network information theory, including multiuser data compression, multiple access channels, broadcast channels, and multiterminal networks. Discussion of philosophical and practical implications of the theory. This course, when combined with EE 112, EE/Ma/CS 127, EE 161, and/or EE 167 should prepare the student for research in information theory, coding theory, wireless communications, and/or data compression. Instructor: Effros.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6); second term. Prerequisites: Ma 2.* This course develops from first principles the theory and practical implementation of the most important techniques for combating errors in digital transmission or storage systems. Topics include algebraic block codes, e.g., Hamming, BCH, Reed-Solomon (including a self-contained introduction to the theory of finite fields); and the modern theory of sparse graph codes with iterative decoding, e.g. LDPC codes, turbo codes, fountain coding. Emphasis will be placed on the associated encoding and decoding algorithms, and students will be asked to demonstrate their understanding with a software project. Instructor: Kostina.

EE 128 ab. Selected Topics in Digital Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: EE 111 and EE 160 or equivalent required, and EE 112 or equivalent recommended.* The course focuses on several important topics that are basic to modern signal processing. Topics include multirate signal processing material such as decimation, interpolation, filter banks, polyphase filtering, advanced filtering structures and nonuniform sampling, optimal statistical signal processing material such as linear prediction and antenna array processing, and signal processing for communication including optimal transceivers. Not offered 2015–16.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6); first term.* For course description, see Applied Physics.

EE/APh 131. Light Interaction with Atomic Systems - Lasers. *9 units (3-0-6); second term. Prerequisites: APh/EE 130.* Light-matter interaction, spontaneous and induced transitions in atoms and semiconductors. Absorption, amplification, and dispersion of light in atomic media. Principles of laser oscillation, generic types of lasers including semiconductor lasers, mode-locked lasers. Frequency combs in lasers. The spectral properties and coherence of laser light. Instructor: Yariv.

APh/EE 132. Special Topics in Photonics and Optoelectronics. *9 units (3-0-6); third term.* For course description, see Applied Physics.

EE/CS/EST 135. Power System Analysis. *9 units (3-3-3); second term. Prerequisites: EE 44, Ma 2, or equivalent.* Phasor representation, 3-phase transmission system, per-phase analysis; power system modeling, transmission line, transformer, generator; network matrix, power flow solution, optimal power flow; Swing equation, stability, protection; demand response, power markets. Instructors: Low.

CS/EE 143. Communication Networks. *9 units (3-3-3).* For course description, see Computer Science.

CMS/CS/EE 144. Networks: Structure Economics. *12 units (3-3-6); second term.* For course description, see Computing and Mathematical Sciences.

CS/EE 145. Projects in Networking. *9 units (0-0-9).* For course description, see Computer Science.

CS/EE 146. Advanced Networking. *9 units (3-3-3).* For course description, see Computer Science.

EE/CNS/CS 148. Selected Topics in Computational Vision. *9 units (3-0-6); third term. Prerequisites: undergraduate calculus, linear algebra, geometry, statistics, computer programming* . The class will focus on an advanced topic in computational vision: recognition, vision-based navigation, 3-D reconstruction. The class will include a tutorial introduction to the topic, an exploration of relevant recent literature, and a project involving the design, implementation, and testing of a vision system. Instructors: Perona.

EE 150. Topics in Electrical Engineering. *Units to be arranged; terms to be arranged.* Content will vary from year to year, at a level suitable for advanced undergraduate or beginning graduate students. Topics will be chosen according to the interests of students and staff. Visiting faculty may present all or portions of this course from time to time. Instructor: Staff.

EE 151. Electromagnetic Engineering. *9 units (3-0-6); third term. Prerequisite: EE 45.* Foundations of circuit theory—electric fields, magnetic fields, transmission lines, and Maxwell's equations, with engineering applications. Instructor: Yang.

EE 153. Microwave Circuits and Antennas. *12 units (3-2-7); third term. Prerequisite: EE 45.* High-speed circuits for wireless communications, radar, and broadcasting. Design, fabrication, and measurements of microstrip filters, directional couplers, low-noise amplifiers, oscillators, detectors, and mixers. Design, fabrication, and measurements of wire antennas and arrays. Instructor: Antsos.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. *12 units (3-3-6); second term.* For course description, see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second terms. Prerequisite: Ph 2 or equivalent.* An overview of the physics behind space remote sensing instruments. Topics include the interaction of electromagnetic waves with natural surfaces, including scattering of microwaves, microwave and thermal emission from atmospheres and surfaces, and spectral reflection from natural surfaces and atmospheres in the near-infrared and visible regions of the spectrum. The class also discusses the design of modern space sensors and associated technology, including sensor design, new observation techniques, ongoing developments, and data interpretation. Examples of applications and instrumentation in geology, planetology, oceanography, astronomy, and atmospheric research. Instructor: van Zyl.

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. *9 units (3-3-3).* For course description, see Geological and Planetary Sciences.

CS/CNS/EE 159. Advanced Topics in Machine Learning. *9 units (3-0-6); third term.* For course description, see Computer Science.

EE 160. Random Variables and Stochastic Processes. *9 units (3-0-6); first term. Prerequisites: Math 2, Math 3.* Introduction to fundamental ideas and techniques of stochastic analysis. Random variables, expectation and conditional expectation, joint distributions, covariance, moment generating functions, central limit theorem, weak and strong laws of large numbers, discrete time stochastic processes, stationarity, power spectral densities, Gaussian processes, Poisson processes. The course develops applications in areas such as communication, signal processing, networks and queues. Instructor: Hassibi.

EE 161. Wireless Communications. *9 units (3-0-6); third term. Prerequisite: EE 160.* This course will cover the fundamentals of wireless channels and channel models, wireless communication techniques, and wireless networks. Topics include statistical models for time-varying narrowband and wideband channels, fading models for indoor and outdoor systems, macro- and microcellular system design, channel access and spectrum sharing using TDMA, FDMA, and CDMA, time-varying channel capacity and spectral efficiency, modulation and coding for wireless channels, antenna arrays, diversity combining and multiuser detection, dynamic channel allocation, and wireless network architectures and protocols. Given in alternate years. Not offered 2015–16.

EE 163 ab. Communication Theory. *9 units (3-0-6); second, third terms. Prerequisites: EE 111; ACM/EE 116 or equivalent.* Mathematical models of communication processes; signals and noise as random processes; sampling; modulation; spectral occupancy; intersymbol interference; synchronization; optimum demodulation and detection; signal-to-noise ratio and error probability in digital baseband and carrier communication systems; linear and adaptive equalization; maximum likelihood sequence estimation; multipath channels; parameter estimation; hypothesis testing; optical communication systems. Part a offered 2015–16; Part b not offered 2015–16. Instructor: Staff.

EE 164. Stochastic and Adaptive Signal Processing. *9 units (3-0-6); third term. Prerequisite: ACM/EE 116 or equivalent.* Fundamentals of linear estimation theory are studied, with applications to stochastic and adaptive signal processing. Topics include deterministic and stochastic least-squares estimation, the innovations process, Wiener filtering and spectral factorization, state-space structure and Kalman filters, array and fast array algorithms, displacement structure and fast algorithms, robust estimation theory and LMS and RLS adaptive fields. Given in alternate years; offered 2015–16. Instructor: Hassibi.

EE/BE/MedE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5); third term. Prerequisite: EE 151 or equivalent.* Topics include Fourier optics, scattering theories, shot noise limit, energy transitions associated with fluorescence, phosphorescence, and Raman emissions. Study of coherent anti-Stokes Raman spectroscopy (CARS), second harmonic generation and near-field excitation. Scattering, absorption, fluorescence, and other optical properties of biological tissues and the changes in these properties during cancer progression, burn injury, etc. Specific optical technologies employed for biomedical research and clinical applications: optical coherence tomography, Raman spectroscopy, photon migration, acousto-optics (and opto-acoustics) imaging, two-photon fluorescence microscopy, and second- and third-harmonic microscopy. Given in alternate years; not offered 2015–16.

EE 167. Data Compression. *9 units (3-0-6); third term. Prerequisite: EE/Ma 126 or instructor's permission.* An introduction to the basic results, both theoretical and practical, of data compression. Review of relevant background from information theory. Fixed model and adaptive Huffman and arithmetic codes. The Lempel-Ziv algorithm and its variants. Scalar and vector quantization, including the Lloyd-Max quantizers, and the generalized Lloyd algorithm. Transform coding. Karhuenen-Loeve and discrete cosine transforms. The bit allocation problem. Subband coding. Practical algorithms for image and video compression. Not offered 2015–16.

ACM/EE 170. Mathematics of Signal Processing. *12 units (3-0-9); third term.* See course description in Applied and Computational Mathematics.

EE/APh 180. Nanotechnology. *6 units (3-0-3); first term.* This course will explore the techniques and applications of nanofabrication and miniaturization of devices to the smallest scale. It will be focused on the understanding of the technology of miniaturization, its history and present trends towards building devices and structures on the nanometer scale. Examples of applications of nanotechnology in the electronics, communications, data storage and sensing world will be described, and the underlying physics as well as limitations of the present technology will be discussed. Instructor: Scherer.

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6).* For course description, see Applied Physics.

EE/BE/MedE 185. MEMS Technology and Devices. *9 units (3-0-6); third term. Prerequisite: APh/EE 9 ab, or instructor's permission.* Micro-electro-mechanical systems (MEMS) have been broadly used for biochemical, medical, RF, and lab-on-a-chip applications. This course will cover both MEMS technologies (e.g., micro- and nanofabrication) and devices. For example, MEMS technologies include anisotropic wet etching, RIE, deep RIE, micro/nano molding and advanced packaging. This course will also cover various MEMS devices used in microsensors and actuators. Examples will include pressure sensors, accelerometers, gyros, FR filters, digital mirrors, microfluidics, micro total-analysis system, biomedical implants, etc. Not offered 2015–16.

CNS/Bi/EE/CS/NB 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

EE/MedE 187. VLSI and ULSI Technology. *9 units (3-0-6); third term. Prerequisites: APh/EE 9 ab, EE/APh 180 or instructor's permission.* This course is designed to cover the state-of-the-art micro/nanotechnologies for the fabrication of ULSI including BJT, CMOS, and BiCMOS. Technologies include lithography, diffusion, ion implantation, oxidation, plasma deposition and etching, etc. Topics also include the use of chemistry, thermal dynamics, mechanics, and physics. Not offered 2015–16.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. *12 units (3-6-3) a = first and second; 9 units (0-9-0) b = second term.* For course description, see Bioengineering.

ACM/CS/EE/CMS 218. Statistical Inference. *3-0-6; third term.* For course description, see Applied and Computational Mathematics.

EE 226. Advanced Information and Coding Theory. *9 units (3-0-6); first term.* A selection of topics in information theory and coding theory not normally covered in EE/Ma 126 ab or EE/Ma/CS 127. These topics include constrained noiseless codes, constructive coding theorems for erasure channels, density evolution, repeat-accumulate and related codes, and network coding. Not offered 2015–16.

EE 243. Special Topics in Laser Physics and Quantum Electronics. *6 units (3-0-3); third term.* The course will cover advanced topics in laser physics and quantum electronics including: Quantum Noise, Coherence, New Resonator concepts, and applications to ultra high speed optical communication, sensing and metrology. The final examination will be in the form of an individualized study assignment. Instructor: Yariv.

EE 291. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering. Primarily for graduate students; students should consult with their advisers.

ENERGY SCIENCE AND TECHNOLOGY

EST 2. Energy and Society. *9 units (3-2-4); third term. Prerequisites: Ph 1ab, Ma 1ab, Ch 1ab.* A discussion of where our energy comes from and how we use it. Resources of oil, coal, natural gas, oil sands, and shale gas. Alternative energy sources: hydroelectric, nuclear, wind, geothermal, solar photovoltaic, and solar thermal. Combustion, steam engines, gas turbines, internal-combustion engines, fuel cells and batteries. The electricity grid and transmission lines, agriculture and biofuels, freight and passenger transportation, and heating and lighting of buildings. Not offered on a pass/fail basis. Satisfies the menu requirement of the Caltech core curriculum. Instructor: Rutledge.

EST/EE/ME 109. Energy Technology and Policy. *9 units (3-0-6); first term. Prerequisites: Ph 1 abc, Ch 1 ab and Ma 1 abc.* A discussion of how energy technology interacts with government policy. Renewable sources and the electricity grid. The shale gas revolution and fracking impacts. Electric vehicles and car mileage standards. Coal mining by mountaintop removal and pollution. Peak oil and the debate on limits to growth. Resource models and climate-change policy. Instructors: Rutledge.

EE/CS/EST 135. Power System Analysis. *9 units (3-3-3); second term.* For course description, see Electrical Engineering.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6).* For course description, see Materials Science.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* Subject matter will change from term to term depending upon staff and student interest, but will generally center on modes of energy storage and conversion. Instructor: Staff.

ENGINEERING (GENERAL)

E 2. Frontiers in Engineering and Applied Science. *1 unit; first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the EAS faculty to discuss his or her area of engineering and group's research at an introductory level. The course can be used to learn more about different areas of study within engineering and applied science. Graded pass/fail. Instructor: Ravichandran.

E 10. Technical Seminar Presentations. *3 units (1-0-2); first, second, third terms. (Seniors required to take E 10 are given priority in registration. NOTE: Those who neither preregister nor attend the organizational meeting may not be permitted to enroll.)* Guidance and practice in organizing and preparing topics for presentation and in speaking with the help of visual aids, including whiteboards, overhead projectors, and video projectors. Instructor: Fender.

E 11. Written Technical Communication in Engineering and Applied Science. *3 units (1-0-2); second, third, fourth terms.* This class provides the opportunity for students to gain experience in technical writing in engineering and applied science. Students will choose a technical topic of interest, possibly based on a previous research or course project, and write a paper in a form that would be appropriate as an engineering report, a technical conference paper, or a peer-reviewed journal paper. The topic of ethical considerations for engineers and scientists as they arise in the publication and peer review process will also be discussed. A Caltech faculty member, a postdoctoral scholar, or technical staff member serves as a technical mentor for each student, to provide feedback on the content and style of the report. Fulfills the Institute scientific writing requirement. *Enrollment is limited to students in E&AS options (and PMA options in fourth term) and priority is given to seniors.* Instructors: Pierce, Readhead, Smith.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6); second term. Prerequisites: none.* This course will examine artists' work with new technology, fabrication methods and media from the late 19th Century to the present. Major artists, exhibitions, and writings of the period will be surveyed. While considering this historical and critical context, students will create their own original new media artworks using technologies and/or fabrication methods they choose. Possible approaches to projects may involve robotics, electronics, computer programming, computer graphics, mechanics and other technologies. Students will be responsible for designing and fabricating their own projects. Topics may include systems in art, the influence of industrialism, digital art, robotics, telematics, media in performance, interactive installation art, and technology in public space. Artists studied may include Eadweard Muybridge, Marcel Duchamp, Vladmir Tatlin, John Cage, Jean Tinguely, Stelarc, Survival Research Laboratories, Lynne Hershman Leeson, Edwardo Kac, Natalie Jeremenjenko, Heath Bunting, Janet Cardiff and others. Instructors: Mushkin.

E 102. Entrepreneurial Development. *9 units (3-0-6); first term.* An introduction to the basics of getting a high-technology business started, including early-stage patent, organizational, legal, and financing issues; growing a company; taking a company public; and mergers and acquisitions. Lectures include presentations by invited experts in various specialties and keynote guest lecturers of national stature in technology start-ups. Only E 102 b will be offered 2015–16. Instructor: Pickar.

E/ME 103. Management of Technology. *9 units (3-0-6); third term.* A course intended for students interested in learning how rapidly evolving technologies are harnessed to produce useful products. Students will work through Harvard Business School case studies, supplemented by lectures to elucidate the key issues. There will be a term project. The course is team-based and designed for students considering working in companies (any size, including start-ups) or eventually going to business school. Topics include technology as a growth agent, financial fundamentals, integration into other business processes, product development pipeline and portfolio management, learning curves, risk assessment, technology trend methodologies (scenarios, projections), motivation, rewards and recognition. Industries considered will include electronics (hardware and software), aerospace, medical, biotech, etc. E 102 and E/ME 105 are useful but not required precursors. Not offered 2015–16.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); second, third terms.* This Product Design class focuses on people with Disabilities and is done in collaboration with Rancho Los Amigos National Rehabilitation Center. Students visit the Center to define products based upon actual stated and observed needs. Designs and testing are done in collaboration with Rancho associates. Speakers include people with assistive needs, therapists and researchers. Classes teach normative design methodologies as adapted for this special area. Instructors: Pickar.

E 110. Principles of University Teaching and Learning in STEM. *2 units (1-0-1); first term.* Research on university-level teaching and learning in Science, Technology, Engineering, and Mathematics (STEM) disciplines has progressed rapidly in recent years; a well-established body of evidence-based principles now exists to inform instructors and students at the undergraduate and graduate levels. Increasingly, future PIs and faculty are called upon to demonstrate knowledge of and ability to apply established teaching and assessment practices, as well as to analyze the efficacy of new approaches. In this course, weekly interactive meetings will provide focused overviews and guided application of key pedagogical research, such as prior knowledge and misconceptions, novice-expert differences, and cognitive development as applied to university teaching. We will also explore emerging university teaching and learning practices and their theoretical basis (e.g., the flipped classroom, online learning). Readings will inform in-class work and students will apply principles to a project of their choice. Instructors: Horii.

E 120. Data Visualization Projects. *6 units (2-0-4); third term.* This course will provide students with a forum for discussing and working through challenges of visualizing students' data using techniques and principles from graphic design, user experience design, and visual practices in science and engineering. Working together, we will help create and edit students' graphics and other visual forms of data to improve understanding. We will consider the strengths and weaknesses of communicating information visually in drawing, design and diagramming forms such as flow charts, brainstorming maps, graphs, illustrations, movies, animation, as well as public presentation materials, depending on the needs of students' projects. Our approach will be derived from design principles outlined by Edward Tufte and others. The course is targeted towards students across disciplines using visual display and exploration in research. There is no pre-requisite, but students should be competent in acquiring and processing data. Instructors: Mushkin and Lombeyda.

ENGLISH

Hum/En 5. Major British Authors. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 6. American Literature and Culture. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 7. Modern European Literature. *9 units (3-0-6).* For course description, see Humanities.

F/En 30. Introduction to Film. *9 units (3-0-6).* For course description, see Film.

En/Wr 84. Writing About Science. *9 units (3-0-6); third term.* Instruction and practice in writing about science and technology for non-specialist audiences. The course considers how to convey complex technical information in clear, engaging prose in a variety of contexts. Readings in different genres (newspaper journalism, creative non-fiction, and advocacy) raise issues for discussion and serve as models for preliminary writing assignments. A more substantial final project will be on a topic and in the genre of the student's choosing. Includes oral presentation. *Satisfies the Institute scientific writing requirement and the option oral communications requirement for humanities majors.* Instructor: Hall, S.

En 85. Writing Poetry. *9 units (3-0-6); third term.* Students will develop their poetic craft by creating poems in a variety of forms. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Hall, J.

En 86. Fiction and Creative Nonfiction Writing. *9 units (3-0-6); second term.* The class is conducted as a writing workshop in the short-story and personal essay/memoir form. Modern literary stories and essays are discussed, as well as the art and craft of writing well, aspects of "the writing life," and the nature of the publishing world today. Students are urged to write fiction or nonfiction that reflects on the nature of life. Humor is welcome, although not genre fiction such as formula romance, horror, thrillers, fantasy, or sci-fi. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Gerber.

En 89. Writing The News - Journalistic Writing. *9 units (3-0-6); third term.* This class explores journalistic writing — writing that pays close attention to fact, accuracy, clarity and precision. It examines various aspects of the craft, such as reporting and interviewing, theme and scene, character and storytelling. It looks closely at how traditional print journalism offers up the news through newspapers - their structure, rules, process and presentation. It looks at new media, its process and principles. It also explores long-form journalistic writing. Students will produce numerous stories and other writing during the class, including profiles, issues, and reviews. Several of these will be offered for publication in The California Tech. There may be visits by professional journalists and off-campus excursions, including an outing to the Los Angeles Times. Instructor: Kipling.

En 98. Reading in English. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in English or American literature, in areas not covered by regular courses. En 98 is intended primarily for English majors and minors. Interested students should confer with an English faculty member and agree upon a topic before registering for the course. Instructor: Staff.

En 99 ab. Senior Tutorial for English Majors. *9 units (1-0-8).* Students will study research methods and write a research paper. Required of students in the English option. Instructor: Staff.

En 103. Introduction to Medieval British Literature. *9 units (3-0-6); first term.* This course offers a tour of major (as well as some minor) genres and works written in Britain prior to 1500. Far from a literary "dark age," the Middle Ages fostered dramatic experiments in narrative form, bequeathing to modern literature some of its best-loved genres and texts. We will practice reading in Middle English-the language of Chaucer and his contemporaries-while we concentrate on the following questions: how did these texts circulate among readers? How do they establish their authority? What kinds of historical and cultural currents to they engage? Texts may include the lives of saints, the confessions of sinners, drama, lyrics, romances, selections from Chaucer's Canterbury Tales, and Malory's Morte Darthur. Readings will be in Middle and modern English. Instructors: Jahner.

En 104. Imagining the Medieval in the Nineteenth Century. *9 units (3-0-6); third term.* Following the Enlightenment and amidst the Industrial Revolution, the late-eighteenth and nineteenth centuries saw a surging interest in the literature, lives, art, and architecture of the Middle Ages. In this course, we will explore how authors represented, invoked, and often idealized the medieval past-with its knights, peasants, saints, and monsters-as a way to think through the challenges-social, literary, political, aesthetic-of their own time. We will read several novels, poems, and treatises, including Henry David Thoreau's essay, "Walking;" Mark Twain's A Connecticut Yankee in King Arthur's Court; Alfred Lord Tennyson's Idylls of the King;

and others. Requirements for the course will include weekly response papers and two essays. Instructors: Saltzman.

En 105. Old English Literature. *9 units (3-0-6); first term.* "Moððe word fræt." Want to learn how to read the riddle that begins with these words? This course will introduce students to Old English: the earliest form of the English language, spoken in England from roughly the years 450 to 1100. In studying the language, we will turn to its diverse and exciting body of literature, including one poem commemorating the brutal defeat by a Viking army and another based on the biblical story of Judith, who tricks the evil king Holofernes into sleeping with her-but not before slicing off his drunken head. We will also read a variety of shorter texts: laws, medical recipes, humorously obscene riddles. Successful completion of the course will give students a richer sense not only of the earliest period of English literature, but also of the English language as it is written and spoken today. No prior experience with Old or Middle English is necessary for this course. Instructors: Saltzman.

En 106. Literature and Law in Medieval England. *9 units (3-0-6); first term.* This course examines one of the most exciting and transformative periods in legal and literary history, the later Middle Ages. In England, this era witnessed the rise of lawyers, the advent of trial by jury, and the amassment of the common law. It saw kings fall, peasants revolt, and religious dissenters condemned for heresy. But it also saw the development of a sophisticated legal system and, alongside it, a burgeoning literary tradition. This class examines that literary tradition while also tracing some key legal developments of the period. We will read poetic texts together with relevant legal materials, including law codes, trial transcripts, and statutes. As we gain a basic introduction to medieval legal topics, we will also consider how poets represent and appropriate law, analyzing, for instance, how the figure of the witness informs genres like romance and hagiography. Certain readings will be in Middle English, but no previous experience with the language is required. Not offered 2015–16.

En 107. Medieval Romance. *9 units (3-0-6); third term.* The medieval term romanz designated both a language, French, and a genre, romance, dedicated to the adventures of knights and ladies and the villains, monsters, magic, and miles that stood in their way. This course explores key examples from the twelfth through the fifteenth centuries, while also examining evolutions in the form. We will consider how romances figured love and desire as well as negotiated questions of law, territory, and cultural difference. Authors and texts may include Chretien de Troyes, Marie de France, Gawain and the Green Knight, Arthurian legends, outlaw tales, and hagiography. Not offered 2015–16.

En 110. Saints, Sinners, and Sexuality in the Medieval World. *9 units (3-0-6); second term.* This course will investigate medieval conceptions of sanctity, transgression, and appropriate behavior for men and women. We will examine institutions as well as individuals, and explore real situations as well as the imaginary realms created in romances and manuscript marginalia. From the earliest Christian martyrs to Joan of Arc, we will investigate a wide range of sources-literary, artistic, and documentary-to get at the often contradictory but always fascinating intersections of faith, gender, and the forbidden in the medieval world. Not offered 2015–16.

En 113 ab. Shakespeare's Career. *9 units (3-0-6); second, third terms.* A survey of Shakespeare's career as a dramatist. The first term will study his comedies and histories; the second, his tragedies and tragicomedies. Students will need to read one play per week. Not offered 2015–16.

En 114 ab. Shakespeare. *9 units (3-0-6); second term.* A close study of Shakespeare's plays with an emphasis on his language, dramatic structures, characters, and themes. Each term will concentrate on a detailed consideration of three or four of Shakespeare's major plays. The first term is not a prerequisite for the second. Not offered 2015–16.

En 118. Classical Mythology. *9 units (3-0-6); third term.* Why did the Greeks and Romans remain fascinated with the same stories of gods and demigods for more than a thousand years? On the other hand, how did they adapt those stories to fit new times and places? Starting with the earliest Greek poems and advancing through classical Athens, Hellenistic Alexandria, and Augustan Rome, we consider the history of writing poetry as a history of reading the past; the course also serves as an excellent introduction to ancient literary history at large. Readings may include Homer's 'Odyssey,' Hesiod, Aeschylus, Euripides, Apollonius Rhodius, Ovid, and Seneca. Instructor: Haugen.

En 119. Displacement. *9 units (3-0-6); third term.* The literary fascination with people who change places, temporarily or permanently, over a short distance or across the globe, in works dating from our lifetimes and from the recent and the remote past. How readily can such stories be compared, how easy is it to apply traditional categories of literary evaluation, and, in the contemporary world, how have poetry and prose fictions about migration survived alongside other media? 21st-century works will receive considerable attention; other readings may include Virgil, Swift, Flaubert, Mann, Achebe, Nabokov, Didion, Morrison. Not offered 2015–16.

En 121. Literature and Its Readers. *9 units (3-0-6); first term.* The course will investigate readers who have made adventurous uses of their favorite works of literature, from Greek antiquity through the 20th century. Sometimes those readers count, at least temporarily, as literary critics, as when the philosopher Aristotle made Sophocles' *Oedipus the King* the central model in his wildly successful essay on the literary form of tragedy. Other readers have been even more experimental, as when Sigmund Freud, studying the same play, made the "Oedipus complex" a meeting point for his theory of psychology, his vision of human societies, and his fascination with literary narrative. It will discuss some basic questions about the phenomenon of literary reading. Does a book have a single meaning? Can it be used rightly or wrongly? Instructor: Haugen.

En 122. Early History of the Novel. *9 units (3-0-6); first term.* The realistic novel is a surprising, even experimental moment in the history of fiction.

How and why did daily life become a legitimate topic for narrative in the 18th century? The realistic turn clearly attracted new classes of readers, but did it also make the novel a better vehicle for commenting on society at large? Why were the formal conventions of realistic writing so tightly circumscribed? Authors may include Cervantes, Defoe, Richardson, Fielding, Sterne, Walpole, Boswell, and Austen. Not offered 2015–16.

En 123. The 19th-Century English Novel. *9 units (3-0-6); third term.* A survey of the 19th-century novel from Austen through Conrad, with special emphasis upon the Victorians. Major authors may include Austen, Shelley, Dickens, Eliot, Thackeray, Gaskell, Brontë, Collins, Trollope, Stoker, Hardy. Not offered 2015–16.

En 124. 20th-Century British Fiction. *9 units (3-0-6); third term.* A survey of the 20th-century British and Irish novel, from the modernist novel to the postcolonial novel. Major authors may include Conrad, Joyce, Woolf, Forster, Lawrence, Orwell, Amis, Lessing, Rushdie. Not offered 2015–16.

En 125. British Romantic Literature. *9 units (3-0-6); second term.* A selective survey of English writing in the late 18th and early 19th centuries. Major authors may include Blake, Wordsworth, Coleridge, Byron, Keats, Percy Shelley, Mary Shelley, and Austen. Particular attention will be paid to intellectual and historical contexts and to new understandings of the role of literature in society. Instructor: Gilmartin.

En 126. Gothic Fiction. *9 units (3-0-6); first term.* The literature of horror, fantasy, and the supernatural, from the late 18th century to the present day. Particular attention will be paid to gothic's shifting cultural imperative, from its origins as a qualified reaction to Enlightenment rationalism, to the contemporary ghost story as an instrument of social and psychological exploration. Issues will include atmosphere and the gothic sense of space; gothic as a popular pathology; and the gendering of gothic narrative. Fiction by Walpole, Shelley, Brontë, Stoker, Poe, Wilde, Angela Carter, and Toni Morrison. Film versions of the gothic may be included. Not offered 2015–16.

En 127. Jane Austen. *9 units (3-0-6); third term.* This course will focus on the major novels of Jane Austen: Northanger Abbey, Sense and Sensibility, Pride and Prejudice, Mansfield Park, Emma, and Persuasion. Film and television adaptations will also be considered, and students may have the opportunity to read Austen's unfinished works, as well as related eighteenth- and nineteenth-century British fiction and non-fiction. Not offered 2015–16.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); third term.* The development of Irish fiction, poetry, and drama from the early 20th-century Irish literary renaissance, through the impact of modernism, to the Field Day movement and other contemporary developments. Topics may include the impact of political violence and national division upon the literary imagination; the use of folk and fairy-tale traditions; patterns of emigration and literary exile; the challenge of the English language and the relation of Irish writing to British literary tradition; and recent treatments of Irish literature in regional, postcolonial, and global terms. Works by Joyce, Yeats, Synge, Friel, O'Brien, Heaney, Boland, and others. Instructor: Gilmartin.

En 129. Enlightenment Fiction. *9 units (3-0-6); second term.* What was the fate of fiction in an Age of Reason? Historians have questioned whether a conventional sense of the Enlightenment adequately accounts for European culture in the 18th century, and the literary imagination can seem particularly unsuited to generalizations about progress, optimism, reason, and social order. This course will consider experimental narratives and philosophical satires from the English and Continental tradition, as well as early Romantic responses to the Enlightenment. Readings may include Defoe, Sterne, Voltaire, Diderot, Mary Shelley, Hoffman, and fairy tales from the brothers Grimm. Not offered 2015–16.

En 131. Poe's Afterlife. *9 units (3-0-6); second term.* This course focuses on Edgar Allan Poe and the considerable influence his works have had on other writers. Authors as diverse as Charles Baudelaire, Jules Verne, Jorge Luis Borges, Vladimir Nabokov, John Barth, and Philip Roth have used Poe's stories as departure points for their own work. We shall begin by reading some of Poe's s classic short stories, including "The Narrative of Arthur Gordon Pym," "The Purloined Letter," and others. We shall then explore how and why Poe's stories have been so important for authors, despite the fact that his reputation as a great American writer, unlike Hawthorne's and Melville's, for example, is a relatively recent phenomenon. Not offered 2015–16.

En 133. 19th-Century American Women Writers. *9 units (3-0-6), second term.* This course will analyze many of the most popular novels written in the 19th century. How might we account for their success in the 19th century and their marginalization (until recently) in the 20th century? Why were so many of these texts "sentimental"? How might we understand the appeal of "sentimental" literature? What are the ideological implications of sentimentalism? Authors may include Stowe, Warner, Cummins, Alcott, Phelps, Fern, etc. Not offered 2015–16.

En 134. The Career of Herman Melville. *9 units (3-0-6), second term.* The course will focus on Melville's works from *Typee* through *Billy Budd*. Special emphasis will be placed on Melville's relations to 19th-century American culture. Not offered 2015–16.

En 136. The Fiction of Charles Dickens. *9 units (3-0-6).* An overview of the Great Inimitable's fiction, concentrating on four texts representative of different phases of his novel-writing career and their relationship to the changing world of Victorian Britain: *Oliver Twist*, *Dombey and Son*, *Bleak House*, *Our Mutual Friend.* Not offered 2015–16.

En 137. African American Literature. *9 units (3-0-6); second term.* This course analyzes some of the great works of American literature written by African Americans. This body of writing gives rise to two crucial questions:

How does African American literature constitute a literary tradition of its own? How is that tradition inextricable from American literary history? From slave narratives to Toni Morrison's *Beloved,* from the Harlem Renaissance to Alice Walker, from Ralph Ellison to Walter Mosley, African American literature has examined topics as diverse and important as race relations, class identification, and family life. We shall analyze these texts not only in relation to these cultural issues, but also in terms of their aesthetic and formal contributions. Not offered 2015–16.

En 138. Twain and His Contemporaries. *9 units (3-0-6); third term.* This course will study the divergent theories of realism that arose in the period after the Civil War and before World War I. Authors covered may include Howells, James, Charlotte Perkins Gilman, Twain, Sarah Orne Jewett, Jacob Riis, Stephen Crane, and W. E. B. DuBois. Not offered 2015–16.

En 141. James and Wharton. *9 units (3-0-6); first term.* The course covers selected novels, short fiction, and nonfiction writings of friends and expatriates Henry James and Edith Wharton. It will consider formal questions of style and genre as well as the literature's preoccupation with describing and defining American modernity, despite the authors' shared ambivalence toward their native country. Students will read as many as, but no more than, five novels. Texts covered may include *The Portrait of a Lady, Daisy Miller, The Ambassadors,* selections from *The Decoration of Houses, The House of Mirth, The Custom of the Country,* and *The Age of Innocence.* Not offered 2015–16.

En 145. American Ethnic Literature. *9 units (3-0-6); second term.* From the idea of the melting pot to contemporary debates about multiculturalism, the costs and benefits of assimilation have been crucial to understanding what it means to be American in the twentieth and twenty-first centuries. We will be reading novels, autobiographies, sociology, and other texts that describe the struggles of newcomers to adapt to an alien culture while also, often, trying to negotiate a meaningful relation to their native culture. Authors covered may include Anzia Yezierska, Maxine Hong Kingston, Frank Chin, Richard Rodriguez, Philip Roth, and T. C. Boyle. Not offered 2015–16.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6); first, second terms.* This course introduces students to Hollywood films and filmmaking during the classical period, from the coming of sound through the '50s. It will cover basic techniques and vocabulary of film analysis, as we learn to think of films as texts with distinctive formal properties. Topics include the rise and collapse of the studio system, technical transformations (sound, color, deep focus), genre (the musical, the melodrama), cultural contexts (the Depression, World War II, the Cold War), audience responses, and the economic history of the film corporations. Terms may be taken independently. Part a covers the period 1927–1940. Part b covers 1941–1960. Not offered 2015–16.

En/F 161. The New Hollywood. *9 units (3-0-6); second term.* This course examines the post-classical era of Hollywood filmmaking with a focus on the late 1960s through the 1970s, a period of significant formal and thematic experimentation. We will study American culture and politics as well as film in this era, as we consider the relation between broader social transformations and the development of new narrative conventions and cinematic techniques. We will pay particular attention to the changing film industry and its influence on this body of work. Films covered may include Bonnie and Clyde, The Wild Bunch, The Last Picture Show, Jaws, and Taxi Driver. Instructor: Jurca.

En 177. History of the English Language. *9 units (3-0-6); first term.* This course introduces students to the historical development of the English language, from its Proto-Indo-European roots through its earliest recorded forms (Old English, Middle English, and Early Modern English) up to its current status as a world language. English is a language that is constantly evolving, and students will gain the linguistic skills necessary for analyzing the features of its evolution. We will study the variation and development in the language over time and across regions, including variations in morphology, phonology, syntax, grammar, and vocabulary. We will also examine sociological, political, and literary phenomena that accompany and shape changes in the language. Not offered 2015–16.

En 178. Medieval Subjectivities. *9 units (3-0-6); second term.* In the seventeenth century, Descartes penned his famous expression "I think therefore I am!" and thus the modern subject was born-or so the simplified story goes. But long before the age of Descartes, the Middle Ages produced an astonishing range of theories and ideas about human selfhood, subjectivity, and interiority. For instance, writing from prison more than one thousand years earlier, Boethius came to realize that what distinguishes a human being from all other creatures is his capacity to "know himself." The meaning of this opaque statement and others like it will command our attention throughout this course, as we explore the diverse, distinctive, and often highly sophisticated notions of subjectivity that developed in the literatures of the Middle Ages. We will take up questions of human agency, free will, identity, self-consciousness, confession, and secrecy as we encounter them in some of the most exciting texts written during the period, including among others) Augustine's Confessions, Prudentius's Psychomachia, the Old English poem The Wanderer, the mystical writings of Margery Kempe and Julian of Norwich, and Chaucer's Troilus and Criseyde. Not offered 2015–16.

En 179. Constituting Citizenship before the Fourteenth Amendment. *9 units (3-0-6); second term.* What can a slave's narrative teach us about citizenship? How did the new nation identify citizens when its Constitution seemed so silent on the matter? And how did one tailor's pamphlet result in one of most massive restrictions of free speech in U.S. history? Our goal over the semester will be to sketch a story of African American literary production from the latter half of the eighteenth century to the Civil War and to tease out, through this literature, developing understandings of citizenship in the United States. We will read letters, poems, sermons, songs, constitutions and bylaws, short stories, and texts that simply defy easy categorization. We will also spend several sessions becoming familiar with key newspapers and magazines-Freedom's Journal, Frederick Douglass's Paper, The Anglo-African Magazine, Christian Recorder, and The Crisis-to deepen our understanding of the kinds of things people were reading and writing on a regular basis and the kinds of arguments they were making. Writers up for discussion may include: Frederick Douglass, James Madison, Harriet Jacobs, Henry David Thoreau, Sojourner Truth, and David Walker. Not offered 2015–16.

En 180. Special Topics in English. *9 units (3-0-6). See registrar's announcement for details.* Instructor: Staff.

En 181. Hardy: The Wessex Novels. *9 units (3-0-6); third term.* This course will examine the body of work that the late Victorian novelist Thomas Hardy published under the general title *The Wessex Novels,* that is, the sequence of works from *Far from the Madding Crowd* to *Jude the Obscure.* The six main novels will be read critically to give a sense of the totality of this greatest British regional novelist's achievement. Not offered 2015–16.

En 182. Literature and the First Amendment. *9 units (3-0-6); third term.* "Freedom of speech," writes Benjamin Cardozo in *Palko v. Connecticut* (1937), "is the matrix, the indispensable condition, of nearly every other form of freedom." We will go inside the matrix, focusing on how it has affected the books we read. This is not a course in constitutional law or political philosophy, but an opportunity to examine how American literary culture has intersected with law and politics. We will investigate the ways in which the meanings of "freedom," what it entails, and who is entitled to it have changed over time. Possible topics include the obscenity trials surrounding Allen Ginsberg's *Howl* and James Joyce's *Ulysses*, crackdowns on anti-war propagandists, and the legal battle between *Hustler* publisher Larry Flynt and televangelist and Moral Majority cofounder Jerry Falwell. Instructor: Hunter.

En 183. Victorian Crime Fiction. *9 units (3-0-6); first term.* In 19th-century Britain, for the first time in human history, more of a nation's citizens came to live in urban areas than in rural ones. This result of the Industrial Revolution produced many effects, but in the fiction of the period, one of the most striking was an obsession with the problem of crime. Victorian authors filled their novels with murder, prisons, poisonings, prostitution, criminals, and the new figure of the detective; in this class we will look at the social history, publishing developments, and formal dilemmas that underlay such a response. Authors studied may include Dickens, Collins, Braddon, Conan Doyle, Chesterton, and Conrad, among others. Instructor: Gilmore.

En 185. Dickens and the Dickensian. *9 units (3-0-6).* The adjective "Dickensian" makes an almost daily appearance in today's newspapers, magazines, and other media sources. It is used to describe everything from outrageous political scandals, to Bollywood musicals, to multiplot novels. But what does the word really mean? And what part of Charles Dickens's output does it refer to? This class will consider some of Dickens's most famous works alongside a series of contemporary novels, all critically described in

"Dickensian" terms. The main concern will be equally with style and form, and 19th-century and present-day circumstances of production (e.g., serialization, mass production, Web publication, etc.). Authors considered (aside from Dickens) may include Richard Price, Zadie Smith, Monica Ali, and Jonathan Franzen. Not offered 2015–16.

En 186. The Novel of Education. *9 units (3-0-6); third term.* What does it mean to be educated? This class will consider this question via a series of novels that take us from secondary school to the university, and from the nineteenth century to the present. Concentrating on British literature, with its compelling tendency to focalize historical anxieties about class, race and social reform through depictions of formal schooling practices, we too will consider these issues as we enter classrooms and eavesdrop on faculty conversations. At the same time, there will be ample scope to engage with more abstract questions about power, pedagogy, and alienation, and we will use our reading's rich stock of schoolyard bullies, boarding school mean girls, struggling scholars and power-mad professors as the concrete anchor for such considerations. Authors read may include Dickens, Bronte, Waugh, Amis, Spark, Lodge, Ishiguro and Zadie Smith. Instructor: Gilmore.

En 190. Chaucer. *9 units (3-0-6); second term.* This course devotes itself to the writings of the diplomat, courtier, bureaucrat, and poet, Geoffrey Chaucer. Best known for the Canterbury Tales, Chaucer also authored dream visions, lyrics, and philosophical meditations. This course will introduce you to some better-known and lesser-known works in the Chaucerian corpus, while also exploring questions central to the production and circulation of literature in the fourteenth and fifteenth centuries. What did it mean to "invent" a literary work in late medieval England? How did Chaucer imagine himself as a writer and reader? What are the hallmarks of Chaucerian style, and how did Chaucer become the canonical author he is today? We will read Chaucer's works in their original language, Middle English, working slowly enough to give participants time to familiarize themselves with syntax and spelling. No previous experience with the language is necessary. Instructor: Jahner.

En 191. Masterworks of Contemporary Latin American Fiction. *9 units (3-0-6); third term.* This course studies Latin America's most influential authors in the 20th and 21st centuries, with a focus on short stories and novellas produced by the region's avant-garde and "boom" generations. Authors may include Allende, Bombal, Borges, García Márquez, Quiroga, Poniatowska, and Vargas Llosa. All readings and discussions are in English. Not offered 2015–16.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. *9 units (3-0-6); second term.* Studies Cervantes's literary masterpiece, Don Quixote, with a view to the great upheavals that shaped the early modern world: Renaissance Europe's discovery of America; feudalism's demise and the rise of mass poverty; Reformation and Counter-Reformation; extermination of heretics and war against infidels; and the decline of the Hapsburg dynasty. The hapless protagonist of Don Quixote calls into question the boundaries between sanity and madness, truth and falsehood, history and fiction, objectivity and individual experience. What might be modern, perhaps even revolutionary, in Cervantes's dramatization of the moral and material dilemmas of his time? Conducted in English. Instructor: Wey-Gomez.

En/H 197. American Literature and the Technologies of Reading. *9 units (3-0-6); second term.* This course explores the material forms of American literature from the colonial era through the nineteenth century. We will study how and by whom books and other kinds of texts were produced, and how these forms shaped and were shaped by readers' engagement with them. Possible topics include the history of such printing technologies as presses, types, paper, ink, binding, and illustration; the business of bookmaking and the development of the publishing industry; the rise of literary authorship; the career of Benjamin Franklin; print, politics, and the American Revolution; and manuscript culture. Instructor: Hunter

ENGLISH AS A SECOND LANGUAGE

Please see page 290 for requirements regarding English competency. All of the following courses are open to international graduate students only.

ESL 101 ab. Oral Communication and Pronunciation. *3 units (3-0-0); first, second terms.* Communication and pronunciation in spoken English. Development of pronunciation, vocabulary, listening comprehension, and accuracy and fluency in speaking. Aspects of American culture will be discussed. The first term is required for all first-year international students designated by the ESL screening process. Passing the class is based on attendance and effort. Graded pass/fail. Instructor: Geasland.

ESL 107. Introductory Writing and Oral Presentation. *Noncredit; offered by announcement; third term.* The exploration of ideas in both oral and written English is crucial in a variety of academic settings. Whether writing a thesis or term paper, undertaking an oral exam, or presenting at a conference or seminar, the organization of ideas is central, of course, but the details of formatting, grammar, logic, word choice and delivery are a close second. This course includes frequent in-class oral presentations by students based on their current research interests, followed by detailed critiques of pronunciation and style and ample opportunity for practice to develop both English confidence and delivery skills. The writing portion of the course includes classroom exercises and editing practice will be based on student writing samples. Here, also, the emphasis will be on content, logic, formatting and grammar, work choices, as well as punctuation. The goals of the course include improvement of confidence and presentation skills, and the ability to communicate clearly and concisely in both oral and written English. Enrollment is limited, with priority given to graduate students. Instructor: Geasland.

ENVIRONMENTAL SCIENCE AND ENGINEERING

ESE 1. Introduction to Environmental Science and Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 1 ab, Ch 1 ab, and Ma 1 ab.* An introduction to the array of major scientific and engineering issues related to environmental quality on a local, regional, and global scale. Fundamental aspects of major environmental problems will be addressed with an overall focus on the dynamic interplay among the atmosphere, biosphere, geosphere, and hydrosphere. Underlying scientific principles based on biology, chemistry, and physics will be presented. Engineering solutions to major environmental problems will be explored. Not offered on a pass/fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Instructor: Leadbetter.

ESE 90. Undergraduate Laboratory Research in Environmental Science and Engineering. *Units by arrangement; any term. Approval of research supervisor required prior to registration.* Independent research on current environmental problems; laboratory or field work is required. A written report is required for each term of registration. Graded pass/fail. Instructor: Staff.

ESE 100. Special Problems in Environmental Science and Engineering. *Up to 12 units by arrangement; any term. Prerequisites: instructor's permission.* Special courses of readings or laboratory instruction. Graded pass/fail. Instructor: Staff.

ESE 101. Earth's Atmosphere. *9 units (3-0-6); first term.* Composition of the atmosphere. Radiative transfer and the greenhouse effect. Scattering and absorption by gases, clouds, and aerosols. Feedbacks due to water vapor, clouds, ice, and vegetation. Transports of energy and momentum and their effects on the surface climate. Chemical reactions in the atmosphere affecting atmospheric ozone and air quality. Instructor: Ingersoll.

ESE 102. Earth's Oceans. *9 units (3-0-6); first term.* Fundamentals of ocean dynamics: Ekman layers, wind-driven gyres, boundary currents, and overturning circulations. Oceanographic observational methods and phenomenology of the distribution of temperature, salinity, and tracers. Ocean biology and chemistry: simple plankton population models, Redfield ratios, air-sea gas exchange, productivity and respiration, weathering inputs, and carbon cycle basics. Fundamentals of past climate changes. Geochemical methods of inferring past ocean behavior, and changes of ocean circulations over Earth's history. Instructor: Adkins.

ESE 103. Earth's Biogeochemical Cycles. *9 units (3-0-6); second term.* Global cycles of carbon, nitrogen and sulfur. Photosynthesis, respiration and net primary production. Soil formation, erosion, and carbon storage. Ecosystem processes, metrics, and function. Nutrient supply and limitation. Microbial processes underlying weathering, decomposition, and carbon remineralization. Stable isotope tracers in the carbon and hydrologic cycles. The human footprint on the Earth. Instructor: Wennberg.

ESE 104. Current Problems in Environmental Science and Engineering. *1 unit; first term.* Discussion of current research by ESE graduate students, faculty, and staff. Instructor: Staff.

Bi/Ge/ESE 105. Evolution. *12 units (3-4-5); second term.* For course description, see Biology.

ESE 106. Research in Environmental Science and Engineering. *Units by arrangement; any term.* Prerequisites: instructor's permission. Exploratory research for first-year graduate students and qualified undergraduates. Graded pass/fail. Instructors: Staff.

ESE 110 abc. Seminar in Environmental Science and Engineering. *1 unit; first, second, third terms.* Seminar on current developments and research in environmental science and engineering. Graded pass/fail. Instructor: Adkins.

Ge/ESE 118. Methods in Data Analysis. *9 units (3-0-6); first term. Prerequisites: Ma 1 or equivalent.* For course description, see Geology.

ESE 130. Atmosphere Dynamics. *9 units (3-0-6); first term. Prerequisites: ESE 101 or instructor's permission.* Introduction to the physical balances and dynamical mechanisms govIntroduction to the dynamics of large-scale flows in the atmosphere. Governing equations and approximations that describe these rotation and stratification dominated flows. Topics include: conservation laws, equations of state, geostrophic and thermal wind balance, vorticity and potential vorticity dynamics, shallow water dynamics, atmospheric waves. Instructor: Bordoni.

ESE 131. Physical Oceanography. *9 units (3-0-6); second term. Prerequisite: ESE 102 or instructor's permission.* Introduction to the physical balances and dynamical mechanisms governing ocean circulations. Topics include: Overview of observation systems; wind-driven planetary gyres and western boundary currents; buoyancy-driven circulations and abyssal flow; energetics of ocean circulations and combined effects of wind and buoyancy driving; meridional overturning circulations; thermocline models; mesoscale eddies; equatorial waves and response to wind driving at the equator; El Niño and the Southern Oscillation. Instructor: Thompson.

ESE 132. Tropical Atmosphere Dynamics. *9 units (3-0-6); third term. Prerequisite: ESE 130 or instructor's permission.* Phenomenological description of tropical atmospheric circulations at different scales, and theories or models that capture the underlying fundamental dynamics, starting from the large-scale energy balance and moving down to cumulus convection and hurricanes. Topics to be addressed include: large-scale circulations such as the Hadley, Walker, and monsoonal circulations, the intertropical convergence zone, equatorial waves, convectively coupled waves, and hurricanes. Given in alternate years; not offered 2015–16.

ESE 133. Large-scale Atmosphere Dynamics. *9 units (3-0-6); second term. Prerequisite: ESE 130 or instructor's permission.* Introduction to the global-scale fluid dynamics of the atmosphere, beginning with an analysis of classical models of instabilities in atmospheric flows and leading to currently unsolved problems. Topics include barotropic Rossby waves and barotropic instability; the quasigeostrophic two-layer model and baroclinic instability; conservation laws for wave quantities and wave-mean flow interaction theory; turbulent fluxes of heat and momentum; geostrophic turbulence; genesis of zonal jets; Hadley cell dynamics. The course focuses on Earth's atmosphere but treats the circulation of Earth's atmosphere as part of a continuum of possible planetary circulations. Not offered 2015–16.

ESE 134. Cloud and Boundary Layer Dynamics. *9 units (3-0-6); third term. Prerequisite: ESE 130 or instructor's permission.* Introduction to the dynamics of clouds and atmospheric boundary layers, from a phenomenological overview of cloud and boundary layer morphologies to closure theories for turbulence and convection. Topics include similarity theories for neutral and thermally stratified boundary layers; dry convective boundary layers; mixed-layer models; stably stratified boundary layers; moist thermodynamics and stability; stratocumulus and trade-cumulus boundary layers; shallow cumulus convection and deep convection. Given in alternate years; not offered 2015–16.

ESE 135. Topics in Atmosphere and Ocean Dynamics. *6 (2-0-4); third term. Prerequisites: ESE 101/102 or equivalent.* A lecture and discussion course on current research in atmosphere and ocean dynamics. Topics covered vary from year to year and may include global circulations of planetary atmospheres, geostrophic turbulence, atmospheric convection and cloud dynamics, wave dynamics and large-scale circulations in the tropics, marine physical-biogeochemical interactions, and dynamics of El Niño and the Southern Oscillation. Instructors: Bordoni, Thompson.

ESE 137. Polar Oceanography. *9 units (3-0-6); third term. Prerequisites: ESE 131 or instructor's permission.* This courses focuses on the high latitude circulation of the Earth's ocean as well as the ocean's interaction with the cryosphere, including glaciers, ice shelves and sea ice. Topics covered include: water mass formation and modification processes, the dynamics of the Southern Ocean's overturning circulation, Arctic circulation, controls on sea distribution, the stability of marine-terminating ice sheets. Given in alternate years, not offered 2015–16.

ESE 138. Ocean Turbulence and Wave Dynamics. *9 units (3-0-6); third term. Prerequisite: ESE 131 or instructor's permission.* Introduction to the dynamics of ocean mixing and transport with a focus on how these processes feed back on large-scale ocean circulation and climate. Topics include: vorticity and potential vorticity dynamics, planetary and topographic Rossby waves, inertia-gravity waves, mesoscale eddies, turbulent transport of tracers, eddy diffusivity in turbulent flows, frontogenesis and submesoscale dynamics, diapycnal mixing. This course will also include a discussion of observational techniques for measuring mesoscale and small-scale processes in the ocean. Given in alternate years; not offered 2015–16.

Ge/ESE 139. Introduction to Atmospheric Radiation. *9 units (3-0-6); third term.* For course description in Geological and Planetary Sciences.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

Ge/ESE 146. Stable isotope biogeochemistry. *9 units (3-0-6); third term. Prerequisites: Ge 140a or equivalent.* For course description, see Geological and Planetary Sciences.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/ESE 150. Planetary Atmospheres. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/ESE 154. Readings in Paleoclimate. *3 units (1-0-2).* For course description, see Geological and Planetary Sciences.

Ge/ESE 155. Paleoceanography. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. *9 units (3-3-3).* For course description, see Geological and Planetary Sciences.

ESE/ChE 158. Aerosol Physics and Chemistry. *9 units (3-0-6); third term; Open to graduate students and seniors with instructor's permission.* Fundamentals of aerosol physics and chemistry; aerodynamics and diffusion of aerosol particles; condensation and evaporation; thermodynamics of particulate systems; nucleation; coagulation; particle size distributions; optics of small particles. Given in alternate years; not offered 2015–16.

ESE/Bi 166. Microbial Physiology. *9 units (3-1-5); first term. Recommended prerequisite: one year of general biology.* A course on growth and functions in the prokaryotic cell. Topics covered: growth, transport of small molecules, protein excretion, membrane bioenergetics, energy metabolism, motility, chemotaxis, global regulators, and metabolic integration. Instructor: Leadbetter.

ESE/Bi 168. Microbial Metabolic Diversity. *9 units (3-0-6); second term. Prerequisites: ESE 142, ESE/Bi 166.* A course on the metabolic diversity of microorganisms. Basic thermodynamic principles governing energy conservation will be discussed, with emphasis placed on photosynthesis and respiration. Students will be exposed to genetic, genomic, and biochemical techniques that can be used to elucidate the mechanisms of cellular electron transfer underlying these metabolisms. Given in alternate years; not offered 2015–16.

Ge/ESE 170. Microbial Ecology. *9 units (3-2-4); third term.* For course description, see Geological and Planetary Sciences.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6); third term. Prerequisite: Ch 1 or equivalent.* A detailed course about chemical transformation in Earth's atmosphere. Kinetics, spectroscopy, and thermodynamics of gas-phase chemistry of the stratosphere and troposphere; sources, sinks, and lifetimes of trace atmospheric species; stratospheric ozone chemistry; oxidation mechanisms in the troposphere. Instructors: Seinfeld, Wennberg.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0); first term. Prerequisite: ESE/Ge/Ch 171 or equivalent.* A lecture and discussion course about active research in atmospheric chemistry. Potential topics include halogen chemistry of the stratosphere and troposphere; aerosol formation in remote environments; coupling of dynamics and photochemistry; development and use of modern remote-sensing and in situ instrumentation. Graded pass/fail. Not offered 2015–16.

ESE/Ch 175. Physical Inorganic Chemistry of Natural Waters. *9 units (3-0-6); second term. Prerequisites: Ch 1 or instructor's permission.* This course will cover selected aspects of the chemistry of natural and engineered aquatic systems. Lectures cover basic principles of physical-organic and physical-inorganicchemistry relevant to the aquatic environment under realistic conditions. Specific topics that are covered include the principles of equilibrium chemistry in natural water, acid-base chemistry of inorganic and organic acids including aquated carbon dioxide, metal-ligand chemistry, ligand substitution kinetics, kinetics and mechanisms of organic and inorganic redox reactions, photochemical transformations of chemical compounds, biochemical transformations of chemical compounds in water and sediments, heterogeneous surface reactions and catalysis. Thermodynamic, transport, kinetics and reaction mechanisms are emphasized. The primary emphasis during the winter term course will be on the inorganic chemistry of natural waters. Instructors: Hoffmann.

ESE/Ch 176. Physical Organic Chemistry of Natural Waters. *9 units (3-0-6); third term.* This course will cover selected aspects of the chemistry of natural and engineered aquatic systems. Lectures cover basic principles of physical-organic and physical-inorganic chemistry relevant to the aquatic environment under realistic conditions. Specific topics that are covered include the principles of equilibrium chemistry in natural water, acid-base chemistry of inorganic and organic acids including aquated carbon dioxide, metal-ligand chemistry, ligand substitution kinetics, kinetics and mechanisms of organic and inorganic redox reactions, photochemical transformations of chemical compounds, biochemical transformations of chemical compounds in water and sediments, heterogeneous surface reactions and catalysis. Thermodynamic, transport, kinetics and reaction mechanisms are emphasized. The primary emphasis during the spring term course will be on the organic chemistry of natural waters emphasizing the fate and behavior of organic compounds and persistent organic pollutants in the global environment. Instructors: Hoffmann.

ESE 200. Advanced Topics in Environmental Science and Engineering. *Units by arrangement; any term.* Course on contemporary topics in environmental science and engineering. Topics covered vary from year to year, depending on the interests of the students and staff.

Ge/Bi/ESE 246. Molecular Geobiology Seminar. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

ESE 300. Thesis Research.

For other closely related courses, see listings under Chemistry, Chemical Engineering, Civil Engineering, Mechanical Engineering, Biology, Geological and Planetary Sciences, Economics, and Social Science.

FILM

F/En 30. Introduction to Film. *9 units (3-0-6).* This course examines film as an art and as an institution from 1895 through the present. Students will acquire the basic vocabulary and techniques of film analysis, focusing on questions of form (mise-en-scène, cinematography, editing, sound) and narrative, as well as an understanding of the historical development of the medium with an emphasis on the American, European, and Asian contexts. Topics will include the early cinema of illusion, the actuality film, the transition to sound, the Hollywood star system, Italian neorealism, the French New Wave, Dogma 95, and Hong Kong action cinema. Not offered 2015–16.

F/Hum 32. Humanities on Film. *3 units (1-1-1); offered by announcement.* A course centered around a series of films (usually five) screened as part of the Caltech film program. Students will be required to attend prefilm lectures and postfilm discussions, to do some reading, and to produce a short paper.

F 104. French Cinema. *9 units (3-0-6); first term.* For description, see L 104.

L/F 109. Introduction to French Cinema from Its Beginning to the Present. *9 units (3-0-6).* For course description, see Languages.

H/F 131. History on Film. *9 units (2-2-5).* For course description, see History.

H/F 132. Nations/Cultures on Film: Japan. *9 units (2-2-5).* For course description, see History.

H/F 133. Topics in Film History. *9 units (2-2-5).* For course description, see History.

H/F 134. The Science Fiction Film. *9 units (2-2-5).* For course description, see History.

H/F 136. Ethnic Visions. *9 units (2-2-5).* For course description, see History.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6).* For course description, see English.

En/F 161. The New Hollywood. *9 units (3-0-6); second term.* For course description, see English.

FRESHMAN SEMINARS

FS 2. Freshman Seminar: The Origins of Ideas. *6 units (2-0-4); second term.* Why do we have 60 minutes in an hour? Why do we use a fork or chopsticks when we eat? Why do we have music? Why do we have sports? The goal of the class is to learn how to enjoy ignorance, be curious and try and discover the origin and the evolutionary processes that led to the ideas and artifacts that are a part of our life. The class is collaborative and interactive: You will teach as much as you will learn - you will learn as much as you will teach. Most importantly, you will realize the fun in discovery and the joy of human interaction. *Freshmen only; limited enrollment.* Instructors: Bruck.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. *6 units (2-0-4); second term.* Powerful new instruments enable astronomers to collect huge volumes of data on billions of objects. As a result, astronomy is changing dramatically: by the end of this decade, most astronomers will probably be analysing data collected in large surveys, and only a few will still be visiting observatories to collect their own data. The tool chest of future astronomers will involve facility with "big data", developing clever queries, algorithms (some based on machine learning) and statistics, and combining multiple databases. This course will introduce students to some of these tools. After "recovering" known objects, students will be unleashed to make their own astronomical discoveries in new data sets. Limited enrollment. Instructors: Kulkarni.

FS/Ph 4. Freshman Seminar: Astrophysics and Cosmology with Open Data. *6 units (3-0-3); first term.* Astrophysics and cosmology are in the midst of a golden age of science-rich observations from incredibly powerful telescopes of various kinds. The data from these instruments are often freely available on the web. Anyone can do things like study x-rays from pulsars in our galaxy or gamma rays from distant galaxies using data from Swift and Fermi; discover planets eclipsing nearby stars using data from Kepler; measure the expansion of the universe using supernovae data; study the cosmic microwave background with data from Planck; find gravitational waves from binary black hole mergers using data from LIGO; and study the clustering of galaxies using Hubble data. We will explore some of these data sets and the science than can be extracted from them. A primary goal of this class is to develop skills in scientific computing and visualization - bring your laptop! Not offered 2015–16.

FS/Ph 9. Freshman Seminar: The Science of Music. *6 units (2-0-4); first term.* This course will focus on the physics of sound, how musical instruments make it, and how we hear it, including readings, discussions, demonstrations, and student observations using sound analysis software. In parallel we will consider what differentiates music from other sounds, and its role psychically and culturally. Students will do a final project of their choice and design, with possibilities including a book review, analysis of recordings of actual musical instruments, or instrument construction and analysis. *Freshmen only; limited enrollment.* Instructor: Politzer.

FS/Ph 11 abc. Freshman Seminar: Research Tutorial. *6 units (2-0-4); second, third terms of freshman year and first term of sophomore year.* A small number of students will be offered the opportunity to enroll in this tutorial, the purpose of which is to demonstrate how research ideas arise, and are evaluated and tested, and how those ideas that survive are developed, This is accomplished by doing individual, original projects. There will be weekly group meetings and individual tutorial meetings with the instructor. Support for summer research at Caltech between freshman and sophomore years will be automatic for those students making satisfactory progress. Graded pass/fail. *Freshmen only; limited enrollment.* Instructor: Phillips.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. (*2-0-4); third term. Prerequisites: Ma 1a, b.* Enzymes are at the heart of biochemistry. We will begin with a down to earth discussion of how, as catalysts, they are used to convert substrate to product. Then we will model their activity by using explicit equations. Under ideal conditions, their dynamics are described by a system of first order differential equations. The difficulty will be seen to stem from them being non-linear. However, under a steady state hypothesis, they reduce to a simpler equation, whose solution can describe the late time behavior. The students will apply it to some specially chosen, real examples. Not offered 2015–16.

FS/Bi 13. Freshman Seminar: In Search of Memory. *6 units (2-0-4); first term.* An exploration of brain function based on weekly readings in an autobiographical account by a Nobel Prize willing neurobiologist. No lectures. Each week there will be reading from chapters of the book plus relevant research papers, discussing trail-blazing neuroscience experiments. Instructor: Pine.

FS/Ph 15. Freshman Seminar: Dance of the Photons. *6 units (2-0-4); second term.* An exploration of experimental Quantum Mechanics from the beginnings to the future, based on weekly readings and class discussion from the book "Dance of the Photons" by Anton Zeilinger, plus other supplementary sources. No lectures. Interferometers, entanglement, teleportation, quantum computation, and other mysteries will be explored. Not Offered in 2015–16.

FS/Ge 16. Freshman Seminar: Earthquakes. *6 units (2-0-4); first term.* Earthquakes and volcanic eruptions constitute some of the world's major natural hazards. What is the science behind prediction and/or rapid response to these events? We will review the current understanding of the science, the efforts that have been made in earthquake and volcano forecasting, and real-time response to these events. We will learn about advances in earthquake preparation in Southern California, and volcanic eruption forecasting and hazard mitigation elsewhere. There is a required field trip to visit faults and volcanoes somewhere in southern California. *Freshmen only; limited enrollment.* Instructor: Stock.

FS 17. Freshman Seminar: The Business Side of Sports. *6 units (2-0-4); second term.* Ken Lewis's Moneyball (2003) attributes the remarkable success of the low-budget Oakland A's in competing against teams with much larger payrolls to their ability to exploit market failure. The purpose of this course is to evaluate the central claims of the Moneyball thesis. Students will read Moneyball, many of the classic essays published by Bill James in the Baseball Abstract, and some of the classic works in decision theory. The course will necessarily focus on the way baseball executives evaluate both highly quantitative and highly subjective information. Freshmen only; limited enrollment. Instructors: Kiewiet and Claire.

GEOLOGICAL AND PLANETARY SCIENCES

Geology, Geobiology, Geochemistry, Geophysics, Planetary Science

Ge 1. Earth and Environment. *9 units (3-3-3); third term.* An introduction to the ideas and approaches of earth and planetary sciences, including both the special challenges and viewpoints of these kinds of science as well as the ways in which basic physics, chemistry, and biology relate to them. In addition to a wide-ranging lecture-oriented component, there will be a required field trip component (two weekend days). The lectures and topics cover such issues as solid earth structure and evolution, plate tectonics, oceans and atmospheres, climate change, and the relationship between geological and biological evolution. Not offered on a pass/fail basis. Instructor: Asimow. *Satisfies the menu requirement of the Caltech core curriculum.*

Ge 10. Frontiers in Geological and Planetary Sciences. *2 units (2-0-0); second term. The course may be taken multiple times.* Weekly seminar by a member of the Division of Geological and Planetary Sciences or a visitor to discuss a topic of his or her current research at an introductory level. The course is designed to introduce students to research and research opportunities in the division and to help students find faculty sponsors for individual research projects. Graded pass/fail. Instructor: Clayton.

Ge 11 a. Introduction to Earth and Planetary Sciences: Earth as a Planet. *9 units (3-3-3); first term.* Systematic introduction to the physical and chemical processes that have shaped Earth as a planet over geological time, and the observable products of these processes - rock materials, minerals, land forms. Geophysics of Earth. Plate tectonics; earthquakes; igneous activity. Metamorphism and metamorphic rocks. Rock deformation and mountain building. Weathering, erosion, and sedimentary rocks. Evolution of land forms in response to wind, water, ice, and tectonic processes. The causes and recent history of climate change. The course includes one three-day field trip and a weekly laboratory section focused on the identification of rocks and minerals and the interpretation of topographic and geological maps. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Instructor: Farley.

Ge 11 b. Introduction to Earth and Planetary Sciences: Earth and the Biosphere. *9 units (3-3-3); second term. Prerequisite: Ch 1 a.* Systematic introduction to the origin and evolution of life and its impact on the oceans, atmosphere, and climate of Earth. Topics covered include ancient Earth surface environments and the rise of atmospheric oxygen. Microbial and molecular evolution, photosynthesis, genes as fossils. Banded iron stones, microbial mats, stromatolites, and global glaciation. Biological fractionation of stable isotopes. Numerical calibration of the geological timescale, the Cambrian explosion, mass extinctions, and human evolution. The course usually includes one major field trip and laboratory studies of rocks, fossils, and geological processes. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Biologists biologists are particularly welcome. Instructors: Fischer, Kirschvink.

Ge/Ay 11 c. Introduction to Earth and Planetary Sciences: Planetary Sciences. *9 units (3-0-6); third term. Prerequisites: Ma 1 ab, Ph 1 ab.* A broad introduction to the present state and early history of the solar system, including terrestrial planets, giant planets, moons, asteroids, comets, and rings. Earth-based observations, observations by planetary spacecraft, study of meteorites, and observations of extrasolar planets are used to constrain models of the dynamical and chemical processes of planetary systems. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Physicists and astronomers are particularly welcome. Instructor: Brown

Ge 11 d. Introduction to Earth and Planetary Sciences: Geophysics. *9 units (3-0-6); second term. Prerequisites: Ch 1, Ma 2 a, Ph 2 a.* An introduction to the geophysics of the solid earth; formation of planets; structure and composition of Earth; interactions between crust, mantle, and core; surface and internal dynamics; mantle convection; imaging of the interior; seismic tomography. Although Ge 11 abcd is designed as a sequence, any one term can be taken as a standalone course. Instructors: Clayton, Gurnis.

FS/Ge 16. Freshman Seminar: Earthquakes. *6 units (2-0-4); first term.* For course description, see Freshman Seminar.

Ge 40. Special Problems for Undergraduates. *Units to be arranged; any term.* This course provides a mechanism for undergraduates to undertake honors-type work in the geologic sciences. By arrangement with individual members of the staff. Graded pass/fail.

Ge 41 abc. Undergraduate Research and Bachelor's Thesis. *Units to be arranged; first, second, third terms.* Guidance in seeking research opportunities and in formulating a research plan leading to preparation of a bachelor's thesis is available from the GPS option representatives. Graded pass/fail.

Ge 101. Introduction to Geology and Geochemistry. *9 units (3-0-6); first term. Prerequisites: graduate standing or instructor's permission.* A broad, high-level survey of geology and geochemistry with emphasis on quantitative understanding. Historical deduction in the geological and planetary sciences. Plate tectonics as a unifying theory of geology. Igneous and metamorphic processes, structural geology and geomorphology; weathering and sedimentary processes. Nucleosynthesis and chemical history of the solar system; distribution of the elements in the earth; isotopic systems as tracers and clocks; evolution of the biosphere; global geochemical and biogeochemical cycles; geochemical constraints on deep Earth structure. One mandatory three-day field trip, selected laboratory exercises, and problem sets. Instructor: Farley.

Ge 102. Introduction to Geophysics. *9 units (3-0-6); second term. Prerequisites: Ma 2, Ph 2, or Ge 108, or equivalents.* An introduction to the physics of the earth. The present internal structure and dynamics of the earth are considered in light of constraints from the gravitational and magnetic fields, seismology, and mineral physics. The fundamentals of wave propagation in earth materials are developed and applied to inferring Earth structure. The earthquake source is described in terms of seismic and geodetic signals. The following are also considered: the contributions that heat-flow, gravity, paleomagnetic, and earthquake mechanism data have made to our understanding of plate tectonics, the driving mechanism of plate tectonics, and the energy sources of mantle convection and the geodynamo. Instructors: Clayton, Gurnis.

Ge 103. Introduction to the Solar System. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Formation and evolution of the solar system. Interiors, surfaces, and atmospheres. Orbital dynamics, chaos, and tidal friction. Cratering. Comets and asteroids. Extrasolar planetary systems. Instructor: Brown.

Ge 104. Introduction to Geobiology. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Lectures about the interaction and coevolution of life and Earth surface environments. We will cover essential concepts and major outstanding questions in the field of geobiology, and introduce common approaches to solving these problems. Topics will include biological fractionation of stable isotopes; history and operation of the carbon and sulfur cycles; evolution of oxygenic photosynthesis; biomineralization; mass extinctions; analyzing biodiversity data; constructing simple mathematical models constrained by isotope mass balance; working with public databases of genetic information; phlyogenetic techniques; microbial and molecular evolution. Instructors: Fischer, Kirschvink.

Bi/Ge/ESE 105. Evolution. *12 units (3-4-5); second term. Prerequisites: Completion of Core Curriculum Courses. Prerequisites: Completion of Core Curriculum Courses.* For course description, see Biology.

Ge 106. Introduction to Structural Geology. *9 units (3-0-6); second term. Prerequisite: Ge 11 ab.* Description and origin of main classes of deformational structures. Introduction to continuum mechanics and its application to rock deformation. Interpretation of the record of deformation of the earth's crust and upper mantle on microscopic, mesoscopic, and megascopic scales. Introduction to the tectonics of mountain belts. Instructor: Avouac.

Ge 108. Applications of Physics to the Earth Sciences. *9 units (3-0-6); first term. Prerequisites: Ph 2 and Ma 2 or equivalent.* An intermediate course in the application of the basic principles of classical physics to the earth sciences. Topics will be selected from: mechanics of rotating bodies, the two-body problem, tidal theory, oscillations and normal modes, diffusion and heat transfer, wave propagation, electro- and magneto-statics, Maxwell's equations, and elements of statistical and fluid mechanics. Instructor: Brown.

Ge 109. Oral Presentation. *5 units (2-0-3); third term.* Practice in the effective organization and delivery of reports before groups. Successful completion of this course is required of all candidates for degrees in the division. Graded pass/fail. Instructors: Bikle, Rossman.

Ge 110. Geographic Information System for Geology and Planetary Sciences. *3 units (0-3-0); first term.* Formal introduction to modern computer-based geospatial analysis. Covers methods and applications of Geographic Information Systems (GIS) in Earth and planetary sciences in the form of practical lab exercises using the ArcGIS software package and a variety of geo-referenced data (Digital Elevation Models, geodetic measurements, satellite images, geological maps). Not offered 2015–16.

Ge 111 ab. Applied Geophysics Seminar and Field Course. *6 units (3-3-0); second term. Prerequisite: instructor's permission. 9 units (0-3-6); spring break, third term. Prerequisite: Ge 111 a.* An introduction to the theory and application of basic geophysical field techniques consisting of a comprehensive survey of a particular field area using a variety of methods (e.g., gravity, magnetic, electrical, GPS, seismic studies, and satellite remote sensing). The course will consist of a seminar that will discuss the scientific background for the chosen field area, along with the theoretical basis and implementation of the various measurement techniques. The 4-5-day field component will be held in spring break, and the data analysis component is covered in Ge 111 b. May be repeated for credit with an instructor's permission. Instructors: Clayton, Simons.

Ge 112. Sedimentology and Stratigraphy. *12 units (3-5-4); first term. Prerequisite: Ge 11 ab.* Systematic analysis of transport and deposition in sedimentary environments and the resulting composition, texture, and structure of both clastic and chemical sedimentary rocks. The nature and genesis of sequence architecture of sedimentary basins and cyclic aspects of sedimentary accumulation will be introduced. Covers the formal and practical principles of definition of stratigraphic units, correlation, and the construction of a geologic timescale. Field trip and laboratory exercises. Instructor: Grotzinger. Given in alternate years; offered 2015–16.

Ge 114 a. Mineralogy. *9 units (3-4-2); first term.* Atomic structure, composition, physical properties, occurrence, and identifying characteristics of the major mineral groups. The laboratory work involves the characterization and identification of important minerals by their physical and optical properties. Instructor: Rossman.

Ge 114 b. Mineralogy Laboratory. *3 units (0-2-1); first term. Prerequisite: concurrent enrollment in Ge 114 a or instructor's permission.* Additional laboratory studies of optical crystallography and the use of the petrographic microscope. Instructor: Rossman.

Ge 115 a. Petrology and Petrography: Igneous Petrology. *9 units (3-3-3); second term. Prerequisites: Ge 114 ab.* Study of the origin, occurrence, tectonic significance and evolution of igneous rocks with emphasis on use of phase equilibria and geochemistry. Given in alternate years; offered 2015–16. Instructors: Stolper.

Ge 115 b. Petrology and Petrography: Metamorphic Petrology. *9 units (3-3-3); second term. Prerequisites: Ge 114 ab.* The mineralogic and chemical composition, occurrence, and classification of metamorphic rocks; interpretation of mineral assemblages in the light of chemical equilibrium and experimental studies. Discussion centers on the use of metamorphic assemblages to understand tectonic, petrologic, and geochemical problems associated with convergent plate boundaries and intrusion of magmas into the continental crust. May be taken before Ge 115 a. Given in alternate years; not offered 2015–16.

Ge 116. Analytical Techniques Laboratory. *9 units (1-4-4); second term. Prerequisites: Ge 114 a or instructor's permission.* Methods of quantitative laboratory analysis of rocks, minerals, and fluids in geological and planetary sciences. Consists of five intensive two-week modules covering scanning electron microscopy (imaging, energy-dispersive X-ray spectroscopy, electron backscatter diffraction); the electron microprobe (wavelength-dispersive X-ray spectroscopy); X-ray powder diffraction; optical, infrared, and Raman spectroscopy; and plasma source mass spectrometry for elemental and radiogenic isotope analysis. Satisfies the Institute core requirement for an additional introductory laboratory course. Instructors: Asimow, Jackson, Rossman.

Ge/Ay 117. Statistics and Data Analysis. *9 units (3-0-6); second term. Prerequisites: CS 1 and instructors permission.* In modern fields of planetary science and astronomy, vast quantities of data are often available to researchers. The challenge is converting this information into meaningful knowledge about the universe. The primary focus of this course is the development of a broad and general tool set that can be applied to the student's own research. We will use case studies from the astrophysical and planetary science literature as our guide as we learn about common pitfalls, explore strategies for data analysis, understand how to select the best model for the task at hand, and learn the importance of properly quantifying and reporting the level of confidence in one's conclusions. Not offered 2015–16.

Ge/ESE 118. Methods in Data Analysis. *9 units (3-0-6); first term. Prerequisites: Ma 1 or equivalent.* Introduction to methods in data analysis. Course will be an overview of different ways that one can quantitatively analyze data, and will not focus on any one methodology. Topics will include linear regression, least squares inversion, Fourier analysis, principal component analysis, and Bayesian methods. Emphasis will be on both a theoretical understanding of these methods and on practical applications. Exercises will include using numerical software to analyze real data. Instructor: Tsai.

Ge 120 a. Field Geology: Introduction to Field Geology. *6 units (1-5-0); third term. Prerequisite: Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106).* A comprehensive introduction to methods of geological field mapping through laboratory exercises in preparation for summer field camp. Laboratory exercises introduce geometrical and graphical techniques in the analysis of geologic maps. Field trips introduce methods of geological mapping. Instructor: Wernicke.

Ge 120 b. Field Geology: Summer Field Camp. *18 units (0-18-0); summer. Prerequisite: Ge 120 a or instructor's permission.* Intensive three-week field course in a well-exposed area of the southwestern United States covering techniques of geologic field observation, documentation, and analysis. Field work begins immediately following Commencement Day in June. Instructor: Wernicke.

Ge 121 abc. Advanced Field Geology. *12 units (0-9-3); first, second, third terms. Prerequisites: Ge 120 or equivalent, or instructor's permission.* Field mapping and supporting laboratory studies in topical problems related to the geology of the southwestern United States. Course provides a breadth of experience in igneous, metamorphic, or sedimentary rocks or geomorphology. Multiple terms of 121 may be taken more than once for credit if taught by different instructors. Instructors: Lamb (a), Grotzinger (b), Stock (c).

Ge 122 abc. Field Geology Seminar. *6 (1-3-2); first, second, or third term. Prerequisites: Ge 11ab or Ge 101, or instructor's permission.* Each term, a different field topic in Southern California will be examined in both seminar and field format. Relevant readings will be discussed in a weekly class meeting. During the 3-day weekend field trip we will examine field localities relevant to the topic, to permit detailed discussion of the observations. Fall term 2015 topic: cataclastic fault rocks, mylonites and pseudotachylytes. Class can be taken more than once because the content is different each time. Graded pass/fail. Instructor: Stock.

Ge 124 a. Paleomagnetism and Magnetostratigraphy. *6 units (0-0-6); third term.* Application of paleomagnetism to the solution of problems in stratigraphic correlation and to the construction of a high-precision geological timescale. A field trip to the southwest United States or Mexico to study the physical stratigraphy and magnetic zonation, followed by lab analysis. Given in alternate years; not offered 2015–16.

Ge 124 b. Paleomagnetism and Magnetostratigraphy *9 units (3-3-3); third term. Prerequisite: Ge 11 ab.* The principles of rock magnetism and physical stratigraphy; emphasis on the detailed application of paleomagnetic techniques to the determination of the history of the geomagnetic field. Given in alternate years; not offered 2015–16.

Ge 125. Geomorphology. *12 units (3-5-4); first term. Prerequisite: Ge 11 a or instructor's permission.* A quantitative examination of landforms, runoff generation, river hydraulics, sediment transport, erosion and deposition, hillslope creep, landslides and debris flows, glacial processes, and submarine and Martian landscapes. Field and laboratory exercises are designed to facilitate quantitative measurements and analyses of geomorphic processes. Given in alternate years; not offered 2015–16.

Ge 126. Topics in Earth Surface Processes. *6 units (2-0-4); second term.* A seminar-style course focusing on a specific theme within geomorphology and sedimentology depending on student interest. Potential themes could include river response to climate change, bedrock erosion in tectonically active mountain belts, or delta evolution on Earth and Mars. The course will consist of student-led discussions centered on readings from peer-reviewed literature. Instructor: Lamb.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6); first term. Prerequisite: instructor's permission.* A survey course in the properties of nuclei, and in atomic phenomena associated with nuclear-particle detection. Topics include rates of production and decay of radioactive nuclei; interaction of radiation with matter; nuclear masses, shapes, spins, and moments; modes of radioactive decay; nuclear fission and energy generation. Given in alternate years; offered 2015–16. Instructor: Burnett.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); third term. Prerequisites: instructor's permission.* Examination of the chemistry of the interstellar medium, of protostellar nebulae, and of primitive solar-system objects with a view toward establishing the relationship of the chemical evolution of atoms in the interstellar radiation field to complex molecules and aggregates in the early solar system that may contribute to habitability. Emphasis will be placed on identifying the physical conditions in various objects, timescales for physical and chemical change, chemical processes leading to change, observational constraints, and various models that attempt to describe the chemical state and history of cosmological objects in general and the early solar system in particular. Given in alternate years; not offered 2015–16.

Ge 131. Planetary Structure and Evolution. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* A critical assessment of the physical and chemical processes that influence the initial condition, evolution, and current state of planets, including our planet and planetary satellites. Topics to be covered include a short survey of condensed-matter physics as it applies to planetary interiors, remote sensing of planetary interiors, planetary modeling, core formation, physics of ongoing differentiation, the role of mantle convection in thermal evolution, and generation of planetary magnetic fields. Instructor: Stevenson.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6); first term. Prerequisite: instructor's permission.* Fundamental aspects of atomic and molecular spectra that enable one to infer physical conditions in astronomical, planetary, and terrestrial environments. Topics will include the structure and spectra of atoms, molecules, and solids; transition probabilities; photoionization and recombination; collisional processes; gas-phase chemical reactions; and isotopic fractionation. Each topic will be illustrated with applications in astronomy and planetary sciences, ranging from planetary atmospheres and dense interstellar clouds to the early universe. Given in alternate years; not offered 2015–16.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6); third term.* Review current theoretical ideas and observations pertaining to the formation and evolution of planetary systems. Topics to be covered include low-mass star formation, the protoplanetary disk, accretion and condensation in the solar nebula, the formation of gas giants, meteorites, the outer solar system, giant impacts, extrasolar planetary systems. Instructor: Knutson.

Ge 136 abc. Regional Field Geology of the Southwestern United States. *3 units (1-0-2); first, second, or third terms, by announcement. Prerequisite: Ge 11 ab or Ge 101, or instructor's permission.* Includes approximately three days of weekend field trips into areas displaying highly varied geology. Each student is assigned the major responsibility of being the resident expert on a pertinent subject for each trip. Graded pass/fail. Instructor: Kirschvink.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6); second term. Prerequisites: Ph 106 abc, ACM 95/100 ab.* A quantitative review of dynamical processes that characterize long-term evolution of planetary systems. An understanding of orbit-orbit resonances, spin-orbit resonances, secular exchange of angular momentum and the onset of chaos will be developed within the framework of Hamiltonian perturbation theory. Additionally, dissipative effects associated with tidal and planet-disk interactions will be considered. Not offered 2015–16.

Ge/ESE 139. Introduction to Atmospheric Radiation. *9 units (3-0-6); third term.* The basic physics of absorption and scattering by molecules, aerosols, and clouds. Theory of radiative transfer. Band models and correlated-k distributions and scattering by cloud and aerosol particles. Solar insolation, thermal emission, heating rates, and examples of applications to climate and remote sensing of Earth, planets and exoplanets. Given in alternate years; offered 2015–16. Instructor: Yung

Ge 140 a. Stable Isotope Geochemistry. *9 units (3-0-6); second term.* An introduction to the principles and applications of stable isotope systems to earth science, emphasizing the physical, chemical and biological processes responsible for isotopic fractionation, and their underlying chemical-physics principles. Topics include the kinetic theory of gases and related isotopic fractionations, relevant subjects in quantum mechanics and statistical thermodynamics, equations of motion of charged particles in electrical and magnetic fields (the basis of mass spectrometry), the photochemistry of isotopic species, and applications to the earth, environmental and planetary sciences. Taught in odd years; alternates with Ge 140b. Not offered 2015–16.

Ge 140 b. Radiogenic Isotope Geochemistry. *9 units (3-0-6); second term.* An introduction to the principles and applications of radiogenic isotope systems in earth science. Topics to be covered include radioactive decay phenomena, geochronometry, isotopes as tracers of solar system and planetary evolution, extinct radioactivities, and cosmogenic isotopes. Instructor: Farley. Taught in even years; alternates with Ge 140a. Offered 2015–16.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4); first term. Prerequisite: Ch 41 a or equivalent.* Main topics include the analysis, properties, sources, and cycling of natural organic materials in the environment, from their production in living organisms to burial and decomposition in sediments and preservation in the rock record. Specific topics include analytical methods for organic geochemistry, lipid structure and biochemistry, composition of organic matter, factors controlling organic preservation, organic climate and CO2 proxies, diagenesis and catagenesis, and biomarkers for ancient life. A laboratory component (three evening labs) teaches the extraction and analysis of modern and ancient organic biomarkers by GC/MS. Class includes a mandatory one-day (weekend) field trip to observe the Monterey Formation. Given in alternate years; not offered 2015–16.

Ge 145. Isotope-Ratio Mass Spectrometry. *9 units (1-4-4); first term.* This class provides a hands-on introduction to the construction and operating principles of instrumentation used for isotope-ratio mass spectrometry. The class is structured as a 1-hour lecture plus 4-hour lab each week examining the major subsystems of an IRMS, including vacuum systems, ionization source, mass analyzer, and detector. Laboratories involve hands-on deconstruction and re-assembly of a retired IRMS instrument to examine its components. Course is limited to 6 students at the discretion of the instructor, with preference given to graduate students using this instrumentation in their research. Instructor: Sessions. Given in alternate years; offered 2015–16.

Ge/ESE 146. Stable Isotope Biogeochemistry. *9 units (3-0-6); third term. Prerequisites: Ge 140a or equivalent.* This course serves as an introduction to the use of stable isotopes in biogeochemistry, and is intended to give interested students the necessary background to understand applications in a variety of fields, from modern carbon cycling to microbial ecology to records of Ancient Earth. Topics include the principles of isotope distribution in reaction networks; isotope effects in enzyme-mediated reactions, and in metabolism and biosynthesis; characteristic fractionations accompanying carbon, nitrogen, and sulfur cycling; and applications of stable isotopes in the biogeosciences. Instructor: Sessions.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6); third term. Prerequisites: ESE 102.* Introduction to chemical oceanography and sediment geochemistry. We will address the question “Why is the ocean salty?” by examining the processes that determine the major, minor, and trace element distributions of seawater and ocean sediments. Topics include river and estuarine chemistry, air/sea exchange, nutrient uptake by the biota, radioactive tracers, redox processes in the water column and sediments, carbonate chemistry, and ventilation. Given in alternate years; not offered 2015–16.

Ge/ESE 150. Planetary Atmospheres. *9 units (3-0-6); second term. Prerequisites: Ch 1, Ma 2, Ph 2, or equivalents.* Origin of planetary atmospheres, escape, and chemical evolution. Tenuous atmospheres: the moon, Mercury, and outer solar system satellites. Comets. Vapor-pressure atmospheres: Triton, Io, and Mars. Spectrum of dynamical regimes on Mars, Earth, Venus, Titan, and the gas giant planets. Instructor: Ingersoll.

Ge 151. Planetary Surfaces. *9 units (3-3-3); first term.* Exogenous (impact cratering, space weathering) and endogenous (tectonic, volcanic, weathering, fluvial, aeolian, and periglacial) processes shape the surfaces of planets. We will review the mechanisms responsible for the formation and modification of the surfaces of solar system bodies, studying both composition and physical processes. Instructor: Ehlmann.

Ge/ESE 154. Readings in Paleoclimate. *3 units (1-0-2); second term. Prerequisite: instructor's permission.* Lectures and readings in areas of current interest in paleoceanography and paleoclimate. Instructor: Adkins.

Ge/ESE 155. Paleoceanography. *9 units (3-0-6); third term. Prerequisites: ESE 102.* Evaluation of the data and models that make up our current understanding of past climates. Emphasis will be placed on a historical introduction to the study of the past ten thousand to a few hundred thousand years, with some consideration of longer timescales. Evidence from marine and terrestrial sediments, ice cores, corals, and speleothems will be used to address the mechanisms behind natural climate variability. Models of this variability will be evaluated in light of the data. Topics will include sea level and ice volume, surface temperature evolution, atmospheric composition, deep ocean circulation, tropical climate, ENSO variability, and terrestrial/ocean linkages. Instructor: Adkins. Given in alternate years; offered 2015–16.

Ge 156. Topics in Planetary Surfaces. *6 units (3-0-3). Offered by announcement only.* Reading about and discussion of current understanding of the surface of a selected terrestrial planet, major satellite, or asteroid. Important "classic" papers will be reviewed, relative to the data that are being returned from recent and current missions. May be repeated for credit.

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. *9 units (3-3-3); third term.* Use of different parts of the electromagnetic spectrum (visible, ultraviolet, infrared, and radio wavelengths) for interpretation of physical and chemical characteristics of the surfaces of Earth and other planets. Topics: interaction of light with materials, spectroscopy of minerals and vegetation, atmospheric removal, image analysis, classification, and multi-temporal studies. This course is complementary to EE 157ab with additional emphasis on applications for geological and environmental problems, using data acquired from airborne and orbiting remote sensing platforms. Students will work with digital remote sensing datasets in the laboratory and there will be one field trip. Instructor: Ehlmann.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6); second term.* Photochemistry of planetary atmospheres, comparative planetology, atmospheric evolution. What makes Earth habitable? Remote sensing of extrasolar planets, biosignatures. Given in alternate years; not offered 2015–16.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aerospace.

Ge 161. Plate Tectonics. *9 units (3-0-6); first term. Prerequisite: Ge 11 ab or equivalent.* Geophysical and geological observations related to plate tectonic theory. Instantaneous and finite motion of rigid plates on a sphere; marine magnetic and paleomagnetic measurements; seismicity and tectonics of plate boundaries; reference frames and absolute plate motions. Interpretations of geologic data in the context of plate tectonics; plate tectonic evolution of the ocean basins. Instructor: Stock.

Ge 162. Seismology. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 ab or equivalent.* Review of concepts in classical seismology. Topics to be covered: basic theories of wave propagation in the earth, instrumentation, Earth's structure and tomography, theory of the seismic source, physics of earthquakes, and seismic risk. Emphasis will be placed on how quantitative mathematical and physical methods are used to understand complex natural processes, such as earthquakes. Instructor: Ampuero.

Ge 163. Geodynamics. *9 units (3-0-6); third term. Prerequisite: Ae/Ge/ME 160 ab.* Quantitative introduction to the dynamics of the earth, including core, mantle, lithosphere, and crust. Mechanical models are developed for each of these regions and compared to a variety of data sets. Potential theory applied to the gravitational and geomagnetic fields. Special attention is given to the dynamics of plate tectonics and the earthquake cycle. Instructor: Gurnis.

Ge 164. Mineral Physics. *9 units (3-0-6); second term. Prerequisites: Ge 11 ad or equivalent, or instructor's permission.* Introduction to the mineral physics of Earth's interior. Topics covered: mineralogy and phase transitions at high pressures and temperatures; elasticity and equations of state; vibrational, electronic, and transport properties; application of mineral physics data to Earth and planetary interiors. Instructor: Jackson.

Ge 165. Geophysical Data Analysis. *9 units (3-0-6); third term. Prerequisites: basic linear algebra and Fourier transforms.* Introduction to modern digital analysis: discrete Fourier transforms, Z-transforms, filters, deconvolution, auto-regressive models, spectral estimation, basic statistics, 1-D wavelets, model fitting via singular value decomposition. Not offered 2015–16.

Ge 166. Hydrology. *9 units (3-0-6); third term. Prerequisites: Math 1 or equivalent.* Introduction to hydrology. Focus will be on how water moves on earth, including in groundwater, rivers, oceans, glaciers, and the atmosphere. Class will be based in fluid mechanics, which will be covered. Specific topics will include the Navier-Stokes equation, Darcy's law, aquifer flow, contaminant transport, turbulent flow, gravity waves, tsunami propagation, geostrophic currents, Ekman transport, glacier flow laws, and the Hadley circulation. Given in alternate years, offered 2015–16. Instructor: Tsai.

Ge 167. Tectonic Geodesy. *9 units (3-0-6); fall term. Prerequisites: a working knowledge of unix/linux or equivalent, linear algebra, and coursework in geophysics.* An introduction to the use of modern geodetic observations (e.g., GPS and InSAR) to constrain crustal deformation models. Secular velocity fields, coseismic and time-dependent processes; volcano deformation and seasonal loading phenomena. Basic inverse approaches for parameter estimation and basic temporal filtering algorithms. Instructor: Simons. Given in alternate years; offered 2015–16.

Ge 168. Crustal Geophysics. *9 units (3-0-6); first term. Prerequisite: ACM 95/100 or equivalent, or instructor's permission.* The analysis of geophysical data related to crust processes. Topics include reflection and refraction seismology, tomography, receiver functions, surface waves, and gravity. Instructor: Clayton. Offered 2015–16.

Ge 169 abcd. Readings in Geophysics. *6 units (3-0-3); first, second, third, fourth terms.* Reading courses are offered to teach students to read critically the work of others and to broaden their knowledge about specific topics. Each student will be required to write a short summary of each paper that summarizes the main goals of the paper, to give an assessment of how well the author achieved those goals, and to point out related issues not discussed in the paper. Each student will be expected to lead the discussion on one or more papers. The leader will summarize the discussion on the paper(s) in writing. A list of topics offered each year will be posted on the Web. Individual terms may be taken for credit multiple times without regard to sequence. Instructor: Staff.

Ge/ESE 170. Microbial Ecology. *9 units (3-2-4); third term. Prerequisites: Either ESE/Bi 166 or ESE/Bi 168.* Structural, phylogenetic, and metabolic diversity of microorganisms in nature. The course explores microbial interactions, relationships between diversity and physiology in modern and ancient environments, and influence of microbial community structure on biogeochemical cycles. Introduction to ecological principles and molecular approaches used in microbial ecology and geobiological investigations. Offered in alternate years, not offered 2015–16.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0).* For course description, see Environmental Science and Engineering.

CE/ME/Ge 173. Mechanics of Soils. *9 units (3-0-6); second term.* For course description, see Civil Engineering.

ME/CE/Ge 174. Mechanics of Rocks. *9 units (3-0-6); third term.* For course description, see Mechanical Engineering.

Ge 177. Active Tectonics. *12 units (3-3-6); third term. Prerequisites: Ge 112 and Ge 106 or equivalent.* Introduction to techniques for identifying and quantifying active tectonic processes. Geomorphology, stratigraphy, structural geology, and geodesy applied to the study of active faults and folds in a variety of tectonic settings. Relation of seismicity and geodetic measurements to geologic structure and active tectonics processes. Review of case studies of selected earthquakes. Instructor: Avouac.

Ge 190. The Nature and Evolution of the Earth. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the earth sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 191. Special Topics in Geochemistry. *Units to be arranged; Offered by announcement only.* Advanced-level discussions of problems of current interest in geochemistry. Students may enroll for any or all terms of this course without regard to sequence. Instructors: Staff.

Ge 192. Special Topics in the Geological Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the geological sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 193. Special Topics in Geophysics. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in geophysics. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 194. Special Topics in the Planetary Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in planetary sciences. Students may enroll for any or all terms of the course without regard to sequence. Instructor: Staff.

Ge 195. Special Topics in Field Geology. *Units to be arranged. Offered by announcement.* Field experiences in different geological settings. Supporting lectures will usually occur before and during the field experience. This course will be scheduled only when special opportunities arise. Class may be taken more than once. Instructor: Staff.

Ge 196. Special Topics in Atmospheres and Oceans. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in atmospheric and ocean sciences. Instructor: Staff.

Ge 197. Special Topics in Geobiology. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the geobiological sciences. Students may enroll for any or all terms of the course without regard to sequence. Instructor: Staff.

Ay/Ge 198. Special Topics in the Planetary Sciences. *9 units (3-0-6); third term.* For course description, see Astrophysics.

Ge 211. Applied Geophysics II. *Units to be arranged. Prerequisite: instructor's permission.* Intensive geophysical field experience in either marine or continental settings. Marine option will include participation in a student training cruise, with several weeks aboard a geophysical research vessel, conducting geophysical measurements (multibeam bathymetry, gravity, magnetics, and seismics), and processing and interpreting the data. Supporting lectures and problem sets on the theoretical basis of the relevant geophysical techniques and the tectonic background of the survey area will occur before and during the training cruise. The course might be offered in a similar format in other isolated situations. The course will be scheduled only when opportunities arise and this usually means that only six months' notice can be given. Auditing not permitted. Class may be taken more than once. Instructors: Stock, Clayton, Gurnis.

Ge 212. Thermodynamics of Geological Systems. *9 units (3-0-6); first term. Prerequisites: Either Ch 21 abc, Ge 115 a, or equivalents.* Chemical thermodynamics as applied to geological and geochemical problems. Classical thermodynamics, including stability criteria, homogeneous and heterogeneous equilibria, equilibria subject to generalized constraints, equations of state, ideal and non-ideal solutions, redox systems, and electrolyte conventions. Brief discussion of statistical foundations and an introduction to the thermodynamics of irreversible processes. Instructor: Asimow. Given in alternate years; offered 2015–16.

Ge 214. Spectroscopy of Minerals. *9 units (3-0-6); third term. Prerequisites: Ge 114 a, Ch 21 ab, or instructor's permission.* An overview of the interaction of minerals with electromagnetic radiation from gamma rays to microwaves. Particular emphasis is placed on visible, infrared, Raman, and Mössbauer spectroscopies as applied to mineralogical problems such as phase identification, chemical analysis, site populations, and origin of color and pleochroism. Given in alternate years; not offered 2015–16.

Ge 215. Topics in Advanced Petrology. *12 units (4-0-8); first term. Prerequisite: Ge 115 ab or instructor's permission.* Lectures, readings, seminars, and/or laboratory studies in igneous or metamorphic petrology, paragenesis, and petrogenesis. The course may cover experimental, computational, or analytical methods. Format and content are flexible according to the needs of the students. Given in alternate years; not offered 2015–16.

Ge 217. Radiogenic Isotopes Seminar. *6 units (3-0-3); second term. Prerequisites: Ge 140 or permission of instructor.* The course deals with advanced topics in radiogenic isotope geochemistry and builds on Ge 140, addressing unconventional applications of radioisotopes as well as treating several conventional radiogenic systems in more detail. Each unit begins with a lecture on the history of the system followed by guided discussion of current developments. Special topics include the history of radiogenic isotope geochemistry at Caltech, U-series dating of sediments, high precision U-Pb and 40Ar/39Ar geochronology, and heavy noble gases. Given in alternate years; not offered 2015–16.

Ge 218. Stable Isotopes Seminar. *6 units (3-0-3); second term. Prerequisites: Ge 140 or permission of instructor.* The course deals with advanced topics in stable isotope geochemistry and builds on Ge 140. The course will explore in depth the theory and applications of a subject in stable isotope geochemistry, selected by consensus of the enrolled students at or before the beginning of term. Example subjects could include: stable isotope thermometry; paleoclimate studies; paleoaltimetry; the early solar system; terrestrial weathering; photochemistry; or biosynthetic fractionations. The class will read and discuss classic papers in that subject area, supplemented with instructor lectures and broader background reading. All participants will lead discussions of papers and present one lecture on a relevant subject. Instructor: Eiler. Given in alternate years; offered 2015–2016.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. *6 units (2-0-4); third term.* For course description, see Civil Engineering.

Ge 232. Chemistry of the Solar System. *9 units (3-0-6); first term. Prerequisites: instructor's permission.* The isotopic and elemental compositions of extraterrestrial materials provide clues to conditions, events, and processes during the formation of the solar system. Specific topics include: solar elemental and isotopic compositions; chronology from short-lived nuclei; the unique role of volatile elements; pre-solar grains from meteorites; chondritic meteorite components as clues to solar nebula and asteroid evolution; interplanetary and comet coma dust; asteroidal igneous rocks; overview of lunar materials. Given in alternate years; not offered 2015–16.

Ge/Bi 244. Paleobiology Seminar. *6 units (3-0-3); third term.* Critical reviews and discussion of classic investigations and current research in paleoecology, evolution, and biogeochemistry. Instructor: Kirschvink.

Ge/Bi/ESE 246. Molecular Geobiology Seminar. *6 units (2-0-4); third term. Recommended preparation: ESE/Bi 166.* Critical reviews and discussion of classic papers and current research in microbiology and geomicrobiology. As the topics will vary from year to year, it may be taken multiple times. Instructor: Orphan.

Ge 261. Advanced Seismology. *9 units (3-0-6); third term.* Continuation of Ge 162 with special emphasis on particular complex problems; includes generalizations of analytical methods to handle nonplanar structures and methods of interfacing numerical-analytical codes in two and three dimensions; construction of Earth models using tomographic methods and synthetics. Requires a class project. Instructor: Helmberger.

Ge 263. Computational Geophysics. *9 units (3-0-6); second term. Prerequisites: introductory class in geophysics, class in partial differential equations, some programming experience.* Finite-difference, pseudo-spectral, finite-element, and spectral-element methods will be presented and applied to a number of geophysical problems including heat flow, deformation, and wave propagation. Students will program simple versions of methods. Given in alternate years; not offered 2015–16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Mechanical Engineering.

Ge 270. Continental Tectonics. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 or ACM 113; Ge 11 ab, Ge 106, Ge 162, or Ge 161.* The nature of nonplate, finite deformation processes in the evolution of the continental lithosphere, using the Alpine orogen as an example. Rheological stratification; isostatic and flexural response to near-vertical loads; rifting and associated basin development; collision and strike-slip tectonics; deep crustal processes. Instructor: Wernicke. Given in alternate years; offered 2015–16.

Ge 277. Active Tectonics Seminar. *6 units (2-0-4); second term.* Discussion of key issues in active tectonics based on a review of the literature. The topic of the seminar is adjusted every year based on students' interest and recent literature. Instructor: Avouac.

Ge 297. Advanced Study. *Units to be arranged.*

Ge 299. Thesis Research. Original investigation, designed to give training in methods of research, to serve as theses for higher degrees, and to yield contributions to scientific knowledge.

HISTORY

Hum/H 1 ab. East Asian History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 2. American History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3 a. European Civilization: The Classical and Medieval Worlds. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3 b. European Civilization: Early Modern Europe. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3 c. European Civilization: Modern Europe. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 4 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 4 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 4 c. Civilization, Science, and Archaeology: The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

H 40. Reading in History. *Units to be determined for the individual by the division. Elective, in any term.* Reading in history and related subjects, done either in connection with the regular courses or independently, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

Art/H 68. Modern Art. *9 units (3-0-6); first term.* For course description, see Art.

Art/H 69. Modernism in the Visual Arts, 1850-1945. *9 units (3-0-6).* For course description, see Art.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6).* For course description, see Engineering.

H 98. Reading in History. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history, in areas not covered by regular courses. Instructor: Staff.

H 99 abc. Research Tutorial. *9 units (1-0-8). Prerequisite: instructor's permission.* Students will work with the instructor in the preparation of a research paper, which will form the basis of an oral examination. Instructor: Staff.

H 108 a. The Early Middle Ages. *9 units (3-0-6); second term.* This course is designed to introduce students to the formative period of Western medieval history, roughly from the fourth through the tenth centuries. It will emphasize the development of a new civilization from the fusion of Roman, Germanic, and Christian traditions, with a focus on the Frankish world. The course focuses on the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 108 b. The High Middle Ages. *9 units (3-0-6); third term.* This course is designed to introduce students to European history between 1000 and 1400. It will provide a topical as well as chronological examination of the economic, social, political, and religious evolution of western Europe during this period, with a focus on France, Italy, England, and Germany. The course emphasizes the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 109. Medieval Knighthood. *9 units (3-0-6); first term.* This course tells the story of the knight from his beginnings in the early Middle Ages, through his zenith in the 11th, 12th, and 13th centuries, to his decline and transformation in the late medieval and early modern periods. The course treats the knight not simply as a military phenomenon but also as a social, political, religious, and cultural figure who personified many of the elements that set the Middle Ages apart. Not offered 2015–16.

H 111. The Medieval Church. *9 units (3-0-6); second term.* This course takes students through the history of the medieval Christian Church in Europe, from its roots in Roman Palestine, through the zenith of its power in the high Middle Ages, to its decline on the eve of the Reformation. The course focuses on the church less as a religion (although it will by necessity deal with some basic theology) than as an institution that came to have an enormous political, social, cultural, and economic impact on medieval life, and for a brief time made Rome once more the mistress of Europe. Not offered 2015–16.

H 112. The Vikings. *9 units (3-0-6); third term.* This course will take on the Scandinavian seafaring warriors of the 8th–11th centuries as a historical problem. What were the Vikings, where did they come from, and how they did they differ from the Scandinavian and north German pirates and raiders who preceded them? Were they really the horned-helmeted, bloodthirsty barbarians depicted by modern popular media and by many medieval chronicles? What effect did they have in their roughly two centuries of raiding and colonization on the civilizations of medieval and ultimately modern Europe? Not offered 2015–16.

H 115 abc. British History. *9 units (3-0-6); first, second, third terms.* The political and cultural development of Great Britain from the early modern period to the twentieth century. H 115 a covers the Reformation and the making of a Protestant state (1500–1700). H 115 b examines the Enlightenment and British responses to revolutions in France and America (1700–1830). H 115 c is devoted to the Victorian and Edwardian eras (1830–1918). H 115 a is not a prerequisite for H 115 b; neither it nor H 115 b is a prerequisite for H 115 c. Not offered 2015–16.

H 118. Histories of Collecting. *9 units (3-0-6); second term.* This course examines the history and theory of collecting, concentrating on collectors, collections, and collecting in the West since the Renaissance. It will include field trips to collections around Los Angeles, including the Huntington Art Gallery and the Museum of Jurassic Technology, and the examination of issues such as forgery and the workings of art markets. Not offered 2015–16.

H/Art 119. Art Worlds. *9 units (3-0-6); third term.* Among theorists and practitioners of art, the "art world" has come to be seen as a central force in the production of contemporary art. But what is the art world? When and how did it come to assume this remarkable importance? Drawing on resources including social history, philosophical aesthetics, artists' writings and anthropological theory, this course will examine crucial moments in the formation and changing conception of the art world. Topics include the relation of art worlds to the valuation, collecting, and market for art; the ambivalent relations of the art world to artistic avant-gardes; and the comparative strength of the art world's position in the age of 21st-century globalization. Objects from local collections, and local collections themselves, will be central to the analysis. The course will include a number of field trips as well as presentations by contemporary artists. Not offered 2015–16.

H 121. American Radicalism. *9 units (3-0-6); offered by announcement.* The course will cover a number of radical social, political, and artistic movements in 20th-century America. A focus on the first two decades of the century will center around the poet, journalist, and revolutionary John Reed and his circle in Greenwich Village. Topics will include their involvement with artistic experimentation, the Industrial Workers of the World, the Mexican Revolution, the Russian Revolution, and the movements for birth control and against American involvement in World War I. Other areas of concentration will be the Great Depression of the '30s, with its leftist political and labor actions, and the freewheeling radicalism of the '60s, including the anti-Vietnam protests, Students for a Democratic Society, and the ethnic struggles for social and political equality. Some reference will be made to the anti-globalization movements of today. Not offered 2015–16.

H 122. Household and Family Forms over Time. *9 units (3-0-6); first term.* This course examines the wide variety of family forms and household structures in past societies, as well as the social, cultural, institutional, and economic variables that influenced them. The course focuses mainly on Europe from about 1600 to the present, as this is the area for which most research has been done, but there will be some discussion of other parts of the world, including Asia, Africa, and North and South America. Special attention is given to comparisons among different societies. Not offered 2015–16.

H/An 123. Anthropological Demography. *9 units (3-0-6); first term.* Birth, death, marriage, and migration are the most basic events in people's lives. These events are shaped by both human biology and cultural contexts. This course combines biological and cultural approaches to the study of human populations. Topics include basic demographic techniques, evolutionary perspectives on human demography, longevity, senescence, kinship, household organization, and nuptiality. Students will explore the roles of culture, ecology, and subsistence in demographic explanation. Emphasis is placed on understanding crosscultural and historical variation in population dynamics. Not offered 2015–16.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6); first term.* Birth, marriage, and death—the most basic events in people's lives—are inextricably linked to larger economic and social phenomena. An understanding of these basic events can thus shed light on the economic and social world inhabited by people in the past. In this course students will be introduced to the sources and methods used by historical demographers to construct demographic measures for past populations. In addition, the course will cover a broad range of problems in historical demography, including mortality crises, fertility control, infant mortality, and the role of economic and social institutions in demographic change. While the emphasis is on societies in the past, there will be some discussion of modern demographic trends in various parts of the world. Not offered 2015–16.

H 125. Soviet Russia. *9 units (3-0-6); first term.* Why was the Russian Revolution of 1917 successful? And how did the Soviet system survive nearly 75 years? These questions will be addressed in the wider context of Russian history, with a focus on political, economic, and social institutions in the pre- and post-revolutionary period. Subjects covered include the ideological underpinnings of Bolshevism, Lenin and the Bolshevik coup, the rise of Stalin, collectivization, socialist realism, the command economy, World War II, the Krushchev 'thaw', dissident culture and the arts, popular culture, and Gorbachev's perestroika. A variety of sources will be used, including secondary historical literature, fiction, film, and art. Instructor: Dennison.

H 128. Sustainability and Conservation in the Early Modern World. *9 units (3-0-6); first term.* Sustainability-from corporate boardrooms to communes, the term has been the subject of protests, marketing campaigns, and government policies. Scientists, activists, and politicians have proposed new methods for achieving it; however, the history of the term remains murky. In this course, we will explore how early modern people understood and regulated resources to try to uncover examples of sustainable farming, forestry, and industry from the past. Unlike many courses that focus on specific regions, we will reach beyond borders to examine the intersections of the modes of regulation of resources in Asia, Europe, and North America during the early modern period. Instructors: Pluymers.

H 129. Rivers and Human History. *9 units (3-0-6); second term.* For thousands of years, rivers have been central to human history. They have served as crucial sources of food and water, the sites for religious and political ceremonies, and corridors for transportation. Rivers have also flooded, become polluted, and even caught fire. In this course we will explore how human beings around the world have attempted to manage rivers and the people who live alongside them examining topics such as damming, diversion, and flood control. We will conclude by examining the history and future of the Los Angeles River and its tributaries, which, as concretized flood control channels, offer a unique example of the transformative power of engineering. For this section, students will take a field trip to explore the Los Angeles River. Instructors: Pluymers.

H 130. Innovative History. *9 units (3-0-6); second term.* In recent years some historians have experimented with new and innovative ways of telling the past-on the printed page, using film and video, and on the Internet. The course will focus on these new approaches to historical presentation and knowledge. Students will read, watch, and interact with various examples of these innovative historical works. They will also be exposed to the critiques of traditional historical writing from philosophers, literary critics, and post-modern theorists, which provide intellectual underpinning for experimenting with new forms of history. Not offered 2015–16.

H/F 131. History on Film. *9 units (2-2-5); second term.* An investigation into the variety of ways history has been and can be represented on the screen. Some terms the focus will be a specific historical period or nation; other terms the focus will be the nature of film as a medium for history and biography. The class will include weekly screenings of films as well as weekly discussion sections. Not offered 2015–16.

H/F 132. Nations/Cultures on Film: Japan. *9 units (2-2-5); third term.* Based upon the premise that a great deal of the history and culture of a nation is inscribed in the dramatic features its film makers produce, the course will each term focus on a single nation and/or culture. Each week there will be a screening, supplemented by appropriate readings dealing with history, culture, and film analysis. During the two hour weekly seminar, students will be expected to discuss the film and the readings, while the instructor will provide additional background material and introduce them to the language of cinema. Possible topics include the United States, Japan, Russia, France, Spain, Germany, and Italy. On occasion the class may deal with particular periods in history (e.g. the Italian Renaissance, Imperial Rome) or with cultures that cross national boundaries, such as the Arab World or Latin America. Students will be expected to write short papers after most screenings and one formal term paper. Not offered 2015–16.

H/F 133. Topics in Film History. *9 units (2-2-5); offered by announcement.* The course will focus each term on one kind of motion picture—either a film genre, or films made by an individual director, or from a single nation or region of the world or particular historical era. Included are weekly screenings, readings on film, a weekly discussion meeting, and a term paper. Not offered 2015–16.

H/F 134. The Science Fiction Film. *9 units (2-2-5); third term.* This course will introduce students to some of the classic works of the science fiction film from the earliest days of cinema until the present. It will analyze aesthetic, historical, and social documents, and will show that such films, while describing alternative, hypothetical, and futurist worlds, also serve as a commentary upon and/or a critique of contemporary (to the film) historical, social, political, and ideological systems and attitudes. Not offered 2015–16.

H 135. War, Conquest, and Empires. *9 units (3-0-6); second term.* This course will use historical examples of war and conquest and ask why some periods of history were times of warfare and why certain countries developed a comparative advantage in violence. The examples will come from the history of Europe and Asia, from ancient times up until World War I, and the emphasis throughout will be on the interplay between politics, military technology, and social conditions. Instructor: Hoffman.

H/F 136. Ethnic Visions. *9 units (2-2-5); offered by announcement.* In recent decades, directors from ethnic minorities that are often un- or misrepresented in mainstream Hollywood films have been making dramatic features depicting the history, problems, and prospects of their own communities. This course will feature a selection of such films by directors from African, Latino, Asian, Muslim, and European American ethnic groups, with an eye toward assessing the similarities and differences in the processes of immigration, acculturation, and Americanization. Not offered 2015–16.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6), second term.* The Russian intelligentsia registered the arrival of modern urban society with a highly articulate sensitivity, perhaps because these changes—industrialization, the breakdown of traditional hierarchies and social bonds, the questioning of traditional beliefs—came to Russia so suddenly. This gives their writings a paradigmatic quality; the modern dilemmas that still haunt us are made so eloquently explicit in them that they have served as models for succeeding generations of writers and social critics. This course explores these writings (in English translation) against the background of Russian society, focusing especially on particular works of Chekhov, Dostoevsky, Goncharov, Tolstoy, and Turgenev. Not offered 2015–16.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

HPS/H 152. Renaissance Anatomy and Botany. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

Art/H 153. The Politics of Representation in American Art, 1935-2000. *9 units (3-0-6); first term.* For course description, see Art History.

Art/H 154. Art and Technology. *9 units (3-0-6); third term.* For course description, see Art History.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6).* For course description, see Art History.

HPS/H 156. The History of Modern Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 161. Selected Topics in History. *9 units (3-0-6)*; offered by announcement. Instructors: Staff, visiting lecturers.

HPS/H 162. Social Studies of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 164. History of Space Exploration. *9 units (3-0-6); first term.* For course description, see History and Philosophy of Science.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 167. Experimenting with History/Historic Experiment. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 172. History of Mathematics: A Global View with Close-ups. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6); second term.* For course description, see History and Philosophy of Science. For course description, see History and Philosophy of Science.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 175. Matter, Motion, and Force: Physical Astronomy from Ptolemy to Newton. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 176. History of Alchemy. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 182. See and Tell: 3-D Models for the Visualization of Complex Concepts From the 16th Century to Modern Times. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. *9 units (3-0-6).* For course description, see Art History.

H 184. Travel, Mobility, Migration. *9 units (3-0-6); third term.* People, objects, and knowledge in the European Age of Revolutions, 1770-1848. The aim of this course is to examine the movement of peoples, cultural artifacts, and the dissemination of different sorts of knowledge, during and after the Revolutionary upheavals and nationalist struggles of the late eighteenth and early nineteenth centuries. Topics will include nationalism and multinational communities; political and intellectual exile; imperial ambition, science and knowledge; the effects of warfare on patterns of migration; looting, theft and cultural property. The class will include a number of in-depth case studies, including Italy and South Asia. Not offered 2015–16.

H/HPS 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. *9 units (3-0-6); first term.* This course explores late medieval European understandings of the origins, structure, and workings of the cosmos in the realms of theology, physics, astronomy, astrology, magic, and medicine. Attention is given to the position of humans as cultural creatures at the intersection of nature and spirit; as well as to the place of Christian Europeans in relation to non-Christians and other categories of outsiders within and beyond Europe. We will examine the knowledge system that anticipated racializing theories in the West. Instructor: Wey-Gomez.

HPS/H 186. The Sciences in the Romantic Era. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 187. The Constitution in the Early Republic. *9 units (3-0-6); first term.* This course will trace many of the major constitutional debates that occurred during the first half-century of U.S. History. We will look to the courts, to the legislatures, to Presidents, and to constitutional theorists of the Early Republic to gain insight into how the first generations of Americans understood their Constitution and the governments and rights it recognized. During this formative period, Americans contemplate the location of sovereignty in a federated republic, the rights and privileges of citizenship, and the role of judicial review in a democratic society. Though we will remain firmly entrenched in the period before the Civil War, we will find that many of the issues that created constitutional strife two centuries ago are still relevant to the constitutional questions of today. Not offered 2015–16.

H 188. Origins of the US Civil War. *9 units (3-0-6); first term.* The purpose of this course is to investigate the various causes of the US Civil War. Students will be exposed to prevailing interpretations, which rely mostly on national frames of reference when identifying the economic, political, and constitutional causes of the Sectional Crisis and War. Half of the term will be devoted to these themes. Subsequently, we will be spending the second half of the term examining recent scholarship that examines the international factors on the brewing Sectional Crisis, from the ramifications of British Emancipation to the fluctuating global cotton market. During the last week, we will discuss these interpretative differences and identify possible avenues of synthesis. Students will leave the course with a thorough understanding of the causes of the Civil War and an introduction to transnational influences on American historical development. Not offered 2015–16.

H/L 191. Perspectives on History through German Literature. *9 units (3-0-6); second term.* Industrialization, economic growth, and democracy came to Germany much later than to England and France, and the forms they took in Germany were filtered through the specific institutional character of Central Europe. German-speaking writers and intellectuals saw these trends from the perspective of indigenous intellectual traditions, and the resulting collisions of values and priorities largely shaped European and American social, political, and literary debates for much of the nineteenth and twentieth centuries. This course explores these writings (in English translation) against the historical background of Central European society, focusing on particular works of Goethe, Hoffmann, Heine, Nietzsche, Kafka, Rilke, and Mann. Instructor: Dennison.

H 192. The Crusades. *9 units (3-0-6); second term.* This course will introduce students to the series of religiously motivated European invasions of the Middle and Near East that began at the end of the eleventh century and that led to the creation of Latin Christian principalities in Palestine. Though the crusading movement came to embroil much of Europe itself, the course will focus strictly on the military expeditions to what the Crusaders called the Holy Land, and the history of the Crusader states up to the point of their destruction at the end of the thirteenth century. The course will be guided by the following questions: how did medieval Christianity justify wars of aggression against foreign peoples and religions? What motivated western Europeans to leave their homes and march into a hostile environment, where they often faced impoverishment if not death and where maintaining a Christian presence was a constant struggle? How did they manage to erect stable political entities in alien territory that lasted as long as they did, and how did they have to adapt their own culture to do so? Finally, how did the native peoples of the regions the Crusaders invaded and conquered—Muslim but also Christian and Jewish — perceive the Crusaders? How did the Crusaders' presence affect life in a region whose populations had their own ancient histories and patterns of life? Not offered 2015–16.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. *9 units (3-0-6).* For course description, see English.

H/HPS 194. Travels, Travelers, and Travel Tales: 1700-1900. *9 units (3-0-6); third term.* This course explores the different and changing forms of travel and its representations in the 18th and 19th centuries. It will examine travels within Europe, in the Middle East and Asia, in Africa and the Pacific, in order to look at different sorts of travel from varying points of view, including travel as recreation, the collection and interpretation of scientific data, the control of resources, and the epistemological claims that underwrite imperialism. Recent critical writings on travel narrative and travel fiction will supplement historical travel texts and images, which may include the Paris Academy's exploration of Peru, Cook's travels to the Pacific, and Darwin's voyage on the Beagle. Not offered 2015–16.

H 195. Vesuvius and Pompeii: Geology, Archaeology and Antiquity from the Enlightenment to the Present. *9 units (3-0-6); first term.* This course examines Vesuvius and Pompeii and the relations between them from the earliest Pompeian discoveries to the present debate about the fate of the buried city, and the plans to cope with an impending Vesuvian eruption. It analyses the changing debates about the volcano - and its place in earth sciences - the development of archaeological techniques and their discoveries, the relationship between a tourist economy and the region, and the public debates about how to deal with disasters and conservation in a rapidly changing political environment. Not offered 2015–16.

En/H 197. American Literature and the Technologies of Reading. *9 units (3-0-6); second term.* For course description, see English.

HPS/H 198. Print In a Global Context, 14th to 19th Centuries. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 201. Reading and Research for Graduate Students. *Units to be determined for the individual by the division.*

HISTORY AND PHILOSOPHY OF SCIENCE

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

HPS 98. Reading in History and Philosophy of Science. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history and philosophy of science, in areas not covered by regular courses. Instructor: Staff.

HPS 102 ab. Senior Research Seminar. *12 units (2-0-10). Offered in any two consecutive terms, by arrangement with HPS faculty.* Under the guidance of an HPS faculty member, students will research and write a focused research paper of 15,000 words (approximately 50 pages). Work in the first term will comprise intensive reading in the relevant literature and/or archival or other primary source research. In the second term, students will draft and revise their paper. Open to seniors in the HPS option and to others by special permission of an HPS faculty member. Instructor: Staff.

HPS 103. Public Lecture Series. *1 unit; first, second, third terms.* Student attend four lectures, featuring speakers from outside Caltech, on topics in the history and philosophy of science. Students may choose from a variety of regularly scheduled HPS lectures, including HPS seminars, Harris lectures, and Munro seminars (history or philosophy of science only). Graded on attendance. *Not available for credit toward the humanities–social science requirement.* Graded pass/fail. Instructors: Visiting lecturers.

HPS 104. Forbidden Knowledge. *9 units (3-0-6).* When and how has the notion of freedom of knowledge and teaching in science emerged? What kinds of restrictions have been placed on scientists, their publications and institutions? Who restrained scientific knowledge of what sorts; for what reasons; and how successfully? These questions will be addressed by looking at some canonical cases in the history of science, such as Copernicus and Galileo. But we will also move into more recent history, discussing work on the atomic bomb, genetic engineering, and global warming. Not offered 2015–16.

HPS 105. Science and Literature. *9 units (3-0-6); second term.* This course explores the relationships between the sciences and the humanities, from the point of view of literary-scientific interactions. Issues to be addressed include the "Two Cultures" debate over the years: Huxley vs. Arnold in the late 19th century; Snow vs. Leavis in the mid 20th century; the Science Wars of the late 20th century. Problems of representing scientific content in literary works and the consequences of examining scientific writing from a literary perspective will also be addressed. Readings will be drawn from a variety of genres, including novels, short stories, poetry, essays, and scientific texts. Not offered 2015–16

HPS/Pl 120. Introduction to Philosophy of Science. *9 units (3-0-6); second term.* An introduction to fundamental philosophical problems concerning the nature of science. Topics may include the character of scientific explanation, criteria for the conformation and falsification of scientific theories, the relationship between theory and observation, philosophical accounts of the concept of "law of nature," causation, chance, realism about unobservable entities, the objectivity of science, and issues having to do with the ways in which scientific knowledge changes over time. Instructor: Eberhardt.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6); second term.* An examination of theories of causation and explanation in philosophy and neighboring disciplines. Topics discussed may include probabilistic and counterfactual treatments of causation, the role of statistical evidence and experimentation in causal inference, and the deductive-nomological model of explanation. The treatment of these topics by important figures from the history of philosophy such as Aristotle, Descartes, and Hume may also be considered. Instructor: Eberhardt.

HPS/Pl 122. Probability, Evidence, and Belief. *9 units (3-0-6); second term.* Philosophical and conceptual issues arising from the study of probability theory and how it relates to rationality and belief. Topics discussed may include the foundations and interpretations of probability, arguments for and against the view that we ought to have personal degrees of belief, rational change in beliefs over time, and the relationship between probability and traditional epistemological topics like evidence, justification, and knowledge. Not offered 2015–16.

HPS/Pl 123. Introduction to the Philosophy of Physics. *9 units (3-0-6); first term. Prerequisites: Ph 1abc or instructor's permission.* This course will examine the philosophical foundations of the physical theories covered in the freshman physics sequence: classical mechanics, electromagnetism, and special relativity. Topics may include: the goals of physics; what laws of nature are; the unification of physical theories; symmetries; determinism; locality; the reality of fields; the arrow of time. Instructors: Sebens.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6); first term.* This course will focus on questions about the nature of space and time, particularly as they arise in connection with physical theory. Topics may include the nature and existence of space, time, and motion; the relationship between geometry and physical space (or space-time); entropy and the direction of time; the nature of simultaneity; and the possibility of time travel. Not offered 2015–16.

HPS/Pl 125. Philosophical Issues in Quantum Physics. *9 units (3-0-6); third term. Prerequisites: Ph 2b or Ph 12b.* This course will focus on philosophical and foundational questions raised by quantum physics. Questions may include: Is quantum mechanics a local theory? Is the theory deterministic or indeterministic? What is the role of measurement and observation? Does the wave function always obey the Schrödinger equation? Does the wave function give a complete description of the state of a system? Are there parallel universes? How are we to understand quantum probabilities? Instructors: Sebens.

HPS/Pl 128. Philosophy of Mathematics. *9 units (3-0-6); third term.* An examination of conceptual issues that arise in mathematics. The sorts of issues addressed may include the following: Are mathematical objects such as numbers in some sense real? How do we obtain knowledge of the mathematical world? Are proofs the only legitimate source of mathematical knowledge? What is the relationship between mathematics and the world? How is it possible to apply abstract theory to the world? Views of major historical figures such as Plato, Hume, Kant, and Mill, as well as of contemporary writers are examined. The course will also examine philosophical issues that arise in particular areas of mathematics such as probability theory and geometry. Not offered 2015–16.

HPS/Pl 129. Introduction to Philosophy of Biology. *9 units (3-0-6); first term.* Philosophical and conceptual issues relating to the biological sciences. Topics covered may include the logical structure of evolutionary theory, units of selection, optimization theory, the nature of species, reductionism, teleological and functional reasoning, and ethical issues arising from contemporary biological research. Not offered 2015–16.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6); second term.* A selection of philosophical issues arising in the biological sciences. Topics will vary by term. Not offered 2015–16.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6); offered by announcement.* An introduction to the mind-body problem. The course attempts, from the time of Descartes to the present, to understand the nature of the mind and its relation to the body and brain. Topics to be addressed may include dualism, behaviorism, functionalism, computationalism, neurophilosophy, consciousness and qualia, scientific psychology vs. "folk" psychology, the nature of emotion, knowledge of other minds. Not offered 2015–16.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6); first term.* An in-depth examination of one or more issues at the intersection of contemporary philosophy and the brain and behavioral sciences. Topics may include the development of a theory of mind and self-representation, theories of representation and neural coding, the nature of rationality, the nature and causes of psychopathology, learning and innateness, the modularity of mind. Instructor: Cowie.

HPS/Pl 135. Moral Philosophy and the Brain. *9 units (3-0-6); first term.* This course will examine the impact of recent advances in neuroscience on moral philosophy. Topics to be addressed include: the evolution of morality and a naturalistic perspective on ethics; the role of brain imaging in adjudicating between deontological vs. consequentialist perspectives on moral decision-making and judgment; the relation between virtue theory and habit systems in the brain; brain imaging of altruism and its implications for egoism, empathy, and moral motivation; moral agency and free will; the neuroscience of distributive justice; the debate regarding the normative significance of neuroscience for moral philosophy. Not offered 2015–16.

HPS/Pl 136. Happiness and the Good Life. *9 units (3-0-6); third term.* This course will critically examine the emerging science of happiness and positive psychology, its philosophical assumptions, methodology, and its role in framing social policy and practice. Topics to be addressed include: the relation between happiness as subjective well-being or life satisfaction and philosophical visions of the good life; the relation between happiness and virtue; the causes of happiness and the role of life experience; happiness and economic notions of human welfare, attempts to measure happiness, and the prospect for an economics of happiness; happiness as a brain state and whether brain science can illuminate the nature of happiness; mental illness and psychiatry in light of positive psychology. Instructors: Quartz.

HPS/Pl 138. Human Nature and Society. *9 units (3-0-6); second term.* This course will investigate how assumptions about human nature shape political philosophy, social institutions, and social policy. The course will begin with a historical perspective, examining the work of such political philosophers as Plato, Locke, Rousseau, and Marx, along with such psychologists as Freud and Skinner. Against this historical perspective, it will then turn to examine contemporary views on human nature from cognitive neuroscience and evolutionary psychology and explore their potential implications for political philosophy and social policy. Among topics to be discussed will be the nature of human sociality and cooperation; economic systems and assumptions regarding production and consumption; and propaganda, marketing, and manipulation. Instructor: Quartz.

HPS/H 152. Renaissance Anatomy and Botany. *9 units (3-0-6); third term.* In this class, "the Renaissance" refers to a cultural movement taking place between roughly 1500 and the early decades of the seventeenth century, where anatomy and botany, and those who studied medicine and natural history, formed a part of this movement. Through lectures, class discussion, videos, and field trips to see books, plants, and art work discussed in class, students will learn about the persistence of ancient forms of knowledge, the relations between art and science, the discovery of the circulation of the blood, the expanding use of physiological experiments, and the rise of a mechanistic understanding of the body during the Renaissance. Instructors: Manning.

HPS/H 156. The History of Modern Science. *9 units (3-0-6); third term.* Selected topics in the development of the physical and biological sciences since the 17th century. Not offered 2015–16.

HPS 157. The Evolution of Knowledge. *9 units (3-0-6); second term.* The course analyzes the history of science from a new perspective, that of an evolution of knowledge. It begins with a discussion of the cognitive, social, and material dimensions of knowledge, introducing basic concepts from cognitive science and sociology. It analyzes current discussions of cultural evolution and their relevance to understanding the history of science. Building on this theoretical introduction, major milestones are reviewed, the origin of science in antiquity, the Scientific Revolution of the early modern period, and the transition from classical to modern science, relying on secondary literature as well as on primary sources. Instructors: Renn.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6); third term.* The birth of modern Western science from 1400 to 1700. The course examines the intellectual revolution brought about by the contributions of Copernicus, Galileo, Descartes, Kepler, Newton, and Harvey, and their relation to major political, social, and economic developments. Not offered 2015–16.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6); second term*. This course examines the growth of science in America after World War II, and its relation to Cold War geopolitics. Topics will include the growth of the American research university; the establishment and role of the national laboratory system; the role of federal funding agencies including ONR, NSF, NIH, and DARPA; and the impact of geopolitical considerations and priorities on scientific research and knowledge. Not offered 2015–16.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6); third term.* An exploration of the most significant scientific developments in the physical sciences, structured around the life and work of Albert Einstein (1879–1955), with particular emphasis on the new theories of radiation, the structure of matter, relativity, and quantum mechanics. While using original Einstein manuscripts, notebooks, scientific papers, and personal correspondence, we shall also study how experimental and theoretical work in the sciences was carried out; scientific education and career patterns; personal, political, cultural, and sociological dimensions of science. Instructor: Kormos-Buchwald.

HPS/H 162. Social Studies of Science. *9 units (3-0-6), third term.* A comparative, multidisciplinary course that examines the practice of science in a variety of locales, using methods from the history, sociology, and anthropology of scientific knowledge. Topics covered include the high-energy particle laboratory as compared with a biological one; Western as compared to non-Western scientific reasoning; the use of visualization techniques in science from their inception to virtual reality; gender in science; and other topics. Instructor: Feingold.

HPS/H 164. History of Space Exploration. *9 units (3-0-6); first term.* This course will cover the entire history of space exploration with a particular focus on the Cold War era. The course will begin with the first dreaming about space travel during the 16th century and end with the rise of new space powers such as China and India. We will consider the political, military, technological, social, and cultural dimensions of space exploration. Topics covered include speculations on why humans were drawn to the cosmos in the first place, the weaponization of space, the popular culture of TV shows (such as Star Trek) and movies (such as the Alien series), the secret Soviet space program, the extraordinary Apollo missions to the Moon, and the International Space Station of the 21st century. Instructors: Siddiqi.

HPS/Pl 165. Selected Topics in Philosophy of Science. *9 units (3-0-6);* offered by announcement. Instructors: Staff, visiting lecturers.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6); second term.* The course develops a framework for understanding the changing relations between science and religion in Western culture since antiquity. Focus will be on the ways in which the conceptual, personal, and social boundaries between the two domains have been reshaped over the centuries. Questions to be addressed include the extent to which a particular religious doctrine was more or less amenable to scientific work in a given period, how scientific activity carved an autonomous domain, and the roles played by scientific activity in the overall process of secularization. Instructor: Feingold.

HPS/H 167. Experimenting with History/Historic Experiment. *9 units (3-0-6); second, third terms.* This course uses a combination of lectures with hands-on laboratory work to bring out the methods, techniques, and knowledge that were involved in building and conducting historical experiments. We will connect our laboratory work with the debates and claims made by the original discoverers, asking such questions as how experimental facts have been connected to theories, how anomalies arise and are handled, and what sorts of conditions make historically for good data. Typical experiments might include investigations of refraction, laws of electric force, interference of polarized light, electromagnetic induction, or resonating circuits and electric waves. We will reconstruct instrumentation and experimental apparatus based on a close reading of original sources. Instructor: Buchwald, J.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6); offered by announcement*. This course covers the development of electromagnetism and thermal science from its beginnings in the early 18th century through the early 20th century. Topics covered include electrostatics, magnetostatics, electrodynamics, Maxwell's field theory, the first and second laws of thermodynamics, and statistical mechanics as well as related experimental discoveries. Not offered 2015–16.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visiting lecturers.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6); second term.* A study of the experimental, mathematical, and theoretical developments concerning light, from the time of Ptolemy in the 2nd century A.D. to the production of electromagnetic optics in the 20th century. Not offered 2015–16.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6); second, third terms. Prerequisite: basic Caltech physics course.* This course covers developments in mechanics, as well as related aspects of mathematics and models of nature, from just before the time of Galileo through the middle of the 18th century, which saw the creation of fluid and rotational dynamics in the hands of Euler and others. Not offered 2015–16.

HPS/H 172. History of Mathematics: A Global View with Close-ups. *9 units (3-0-6); offered by announcement.* The course will provide students with a brief yet adequate survey of the history of mathematics, characterizing the main developments and placing these in their chronological, cultural, and scientific contexts. A more detailed study of a few themes, such as Archimedes' approach to infinite processes, the changing meanings of "analysis" in mathematics, Descartes' analytic geometry, and the axiomatization of geometry c. 1900; students' input in the choice of these themes will be welcomed. Not offered 2015–16.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6); second term.* This course examines developments in chemistry from medieval alchemy to the time of Lavoisier and Dalton. It will examine the real content of alchemy and its contributions to modern science, as well as how to decode its bizarre language; chemistry's long quest for respect and academic status; the relations of chemistry with metallurgy, medicine, and other fields; and the content and development of the chemical theories and the chemical laboratory and its methods. Not offered 2015–16.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6); third term.* The course will highlight the background and some of the landmarks in the evolution of Greek astronomy from its tentative beginnings in the 5th century B.C., to its culmination in the work of Ptolemy in the 2nd century A.D. Not offered 2015–16.

HPS/H 175. Matter, Motion, and Force: Physical Astronomy from Ptolemy to Newton. *9 units (3-0-6); second term.* The course will examine how elements of knowledge that evolved against significantly different cultural and religious backgrounds motivated the great scientific revolution of the 17th century. Not offered 2015–16.

HPS/H/Pl 176. History of Alchemy. *9 units (3-0-6); third term.* Alchemy, long considered one of history's "losers," has recently acquired a new and very different prominence among historians as a forerunner of experimental science in general and of chemistry in particular. This course surveys the field of alchemy over its main period of development, considering cases from the ancient world, medieval Islam and Christendom, and early modern Europe. The goal is to chart the evolution of alchemical theory and practice from its inception until the period of its decline at the end of the seventeenth century. Not offered 2015–16.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6); second term*. Galileo's discoveries with the telescope and arguments for the heliocentric theory radically transformed the System of the World, as it was called, and resulted in his being brought before the Inquisition, the most famous single event in the history of science. The readings will be Galileo's *Sidereal Messenger*, *Letters on Sunspots*, *The Assayer*, *Dialogue on the Two Great Systems of the World*, and documents concerned with Galileo's conflicts with the Church in 1616 and 1633. Not offered 2015–16.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* This course will examine the interplay between the theoretical understanding of physical nature and the philosophical definition of reliable knowledge. It will investigate this intellectual interplay in the work of Galileo, Descartes, Newton, Hume, Maxwell, and Einstein. Not offered 2015–16.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* From treatises about geography and astronomy to the history of plants and animals, early modern Natural philosophy provided an astonishingly broad background of research agendas. The course will examine the manner in which observations were carried out and evidence weighed, both in university settings and in the field. Topics to be addressed include the changing perceptions regarding the reliability of the senses; the contribution of instruments to accumulation of reliable knowledge; the standardization of data and its presentation; and the emergence of new argumentative strategies. Not offered 2015–16.

HPS/H 182. See and Tell: 3-D Models for the Visualization of Complex Concepts from the 16th century to modern times. *9 units (3-0-6); first term.* Early modern artists and scholars of all disciplines routinely built three-dimensional objects in order to represent complex concepts and appearances. Some rendered visible abstract formulas in geometrical forms like the movement of the stars; others schematized complex work-flows like drainage systems, or the geographical conditions on Earth; still others proposed costly projects, such as the cupola of St. Peter in Rome, on the basis of a model. These models-many of which still survive-were constructed according to precise rules and regulations, as well as personal taste. The course will offer an introduction to the significance of three-dimensional models in the early modern period, and the manner in which they were crafted and used by artists, physicians, and natural philosophers. Not offered 2015–16.

Pl/HPS 183. Bioethics. *9 units (3-0-6); offered by announcement.* For course description, see Philosophy.

H/HPS 185. Angels and Monsters. *9 units (3-0-6).* For course description, see History.

HPS/H 186. The Sciences in the Romantic Era. *9 units (3-0-6); third term*. This course aims at introducing students to problems, methods, and resources in European science during the era of Romanticism (c. 1780–1830). The Romantic movement embraced the sciences as well as literature, theology, and the arts, and sought to unite them into a comprehensive program of understanding nature based on experimentation and speculative philosophy. Scientists of the Romantic era have addressed fundemental concerns about scientific manipulations of nature that have, in a different form, resurfaced in the later part of the 20th century. Romanticism addresses major themes in the self-awareness of scientists and their perception in society, and it contributed to the emergence of new research fields and scientific institutions to accommodate nationalistic claims. Not offered 2015–16.

HPS/Pl 188. The Evolution of Cognition. *9 units (3-0-6); third term.* By many measures, *Homo sapiens* is the most cognitively sophisticated animal on the planet. Not only does it live in a huge variety of habitats, and not only has it transformed its environment in unprecedented ways, but it is also responsible for such cultural artifacts as language, science, religion, and art. These are achievements that other species, however successful they may be in other respects, have not accomplished. This course investigates the cognitive, behavioral, and environmental bases for humans' surprising cultural dominance of our planet. Possible topics include the evolution of language, the evolution of morality, the evolution of religion, the evolution of cooperation, and the advent of technology, math, science, and the Internet. Contact the instructor to find out what the topic in any given term is. Not offered 2015–16.

H/HPS 194. Travels, Travelers, and Travel Tales: 1700-1900. *9 units.* For course description, see History.

HPS/H 196. Science in Popular Culture. *9 units (3-0-6); third term.* This course will be a historical survey of the intersection between science and popular culture. As such, our goal will be to explore and understand popular science as a historical phenomenon. The course will trace the evolution of popular science in the Western world through important transformations in the modern era, beginning with the rise of a distinct category of "popular science" during the Victorian Era and then moving through to the present day. During the term, we will study a variety of popular scientific forms, such as science fiction, magazines, comics, graphic novels, sci-fi movies, and TV shows. Students will be required to engage in critical analysis of all the assigned readings and actively participate in an online blog. Instructors: Siddiqi.

HPS/H 198. Print In a Global Context, 14th to 19th Centuries. *9 units (3-0-6); third term.* New types of media came into being during the 14th and 15th centuries, leading eventually to a revolution of communication from the 16th century, with the coming of the printing press. This course offers an advanced approach to the variety and power of media, by following text culture in a global perspective before and after the introduction of the printing press by Johannes Gutenberg in the second half of the 15th century. Important issues concern the role of paper, the techniques of producing books and newspapers or pamphlets, the function of illustrations, and finally practices of selling, reading and manipulating information all over the world. The course covers print cultures in Asia, The Ottoman Empire, the Mediterranean, Northern Europe, and the Atlantic World. Not offered 2015–16.

HUMANITIES

Hum/H 1 ab. East Asian History. *9 units (3-0-6); offered by announcement.* Late imperial values, institutions, and behaviors and their evolution in the 19th and 20th centuries. Hum/H 1 a will deal largely with China, and Hum/H 1 b with Japan. The readings will consist of selected thematic texts as well as a chronological textbook. Each term is independent of the other, and students will normally take only one of the two terms. Not offered 2015–16.

Hum/H 2. American History. *9 units (3-0-6); offered by announcement.* Among the major events, trends, and problems of our country's history are the American Revolution, the framing and development of the Constitution, wars, slavery and emancipation, ethnic and gender relations, immigration, urbanization, westward conquest, economic fluctuations, changes in the sizes and functions of governments, foreign relations, class conflicts, domestic violence, and social and political movements. Although no one course can treat all of these themes, each freshman American history course will deal with two or more of them. How have American historians approached them? What arguments and evidence have scholars offered for their interpretations and how can we choose between them? In a word, what can we know about our heritage? Instructor: Kousser.

Hum/H 3 a. European Civilization: The Classical and Medieval Worlds. *9 units (3-0-6); offered by announcement.* Will survey the evolution of Mediterranean and European civilization from antiquity through the end of the Middle Ages. It will emphasize the reading and discussion of primary sources, especially but not exclusively literary works, against the backdrop of the broad historical narrative of the periods. The readings will present students with the essential characteristics of various ancient and medieval societies and give students access to those societies' cultural assumptions and perceptions of change. Instructor: Brown.

Hum/H 3 b. European Civilization: Early Modern Europe. *9 units (3-0-6); offered by announcement.* Will survey the evolution of European civilization from the 14th century to the early 19th century. The topics covered will depend on the individual instructor, but they will include some of the major changes that transformed Western civilization in the early modern period, such as the Renaissance, the Reformation, the rise of sovereign states and the concomitant military revolution, the Scientific Revolution and the Enlightenment, and the French and industrial revolutions. Readings will include major works from the period, as well as studies by modern historians. Instructors: Wey-Gomez, Hoffman.

Hum/H 3 c. European Civilization: Modern Europe. *9 units (3-0-6); offered by announcement.* Will introduce students to major aspects of the politics and culture of modernity that have profoundly transformed Western society and consciousness from the French Revolution to the contemporary era. A variety of historical, literary, and artistic works will be used to illuminate major social, intellectual, and cultural movements. The focus will be on significant and wide-ranging historical change (e.g., the industrial revolution, imperialism, socialism, fascism); on cultural innovation (e.g., modernism, impressionism, cubism); and on the work of significant thinkers. Instructors: Kormos-Buchwald, Dennison.

Hum/H 4 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. *9 units (3-0-6); offered by announcement.* This course will introduce students to the early development of civilization in Mesopotamia and Egypt from 4000 B.C.E. through 1000 B.C.E. Origins of agriculture and writing, the evolution of the city, and the structures of the Mesopotamian economy and social order will be discussed. Comparison with contemporary developments in Egypt during the Old and Middle Kingdoms may include a reading of Gilgamesh from 3000 B.C.E. and of the Egyptian Tale of Sinuhe. The course concludes with a discussion of life during the late Bronze Age. Focus will be on life as it was lived and experienced by many groups in pre-classical antiquity rather than on kings and dynasties. Not offered 2015–16.

Hum/H 4 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. *9 units (3-0-6); offered by announcement.* Connections in antiquity between astrology and astronomy, early theories of light, Islamic science, new concepts of knowledge during the European Middle Ages and Renaissance, the early laboratory, the development of linear perspective, the origins of the Copernican and

Keplerian systems of astronomy, and the science of Galileo. Instructor: Buchwald, J.

Hum/H 4 c. Civilization, Science, and Archaeology: The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. *9 units (3-0-6); offered by announcement.* The civilizations of Egypt and Mesopotamia gave rise to complex forms of religious practices connected to the social order, moral behavior, and the afterlife. The course examines the origins of concepts of moral death and of sin as a violation of cosmic order in antiquity, the nature of polytheism, and the manner in which monotheism arose out of it. In addition to historical analyses the course includes readings by anthropologists who have studied cult structures as well as contemporary theories by evolutionary psychologists. Not offered 2015–16.

Hum/En 5. Major British Authors. *9 units (3-0-6); offered by announcement.* This course will introduce students to one or more of the genres of English literature, including poetry, drama, and prose fiction, by studying major authors from different periods. Sometimes the course will cover a wide range of authors, while at others it will concentrate on a few. Authors might include Chaucer, Shakespeare, Milton, Austen, George Eliot, or Joyce. Instructors: Gilmore, Haugen, Pigman, Jahner, Saltzman.

Hum/En 6. American Literature and Culture. *9 units (3-0-6); offered by announcement.* Studies of American aesthetics, genres, and ideas from the birth of the nation to the present. Students will be introduced to the techniques of formal analysis. We will consider what constitutes evidence in relation to texts and how to develop a persuasive interpretation. Topics may include *Nature's Nation*, slavery and its aftermath, individualism and the marketplace, the "New Woman," and the relation between word and image. Instructors: Hunter, Weinstein, Jurca.

Hum/En 7. Modern European Literature. *9 units (3-0-6); offered by announcement.* An introduction to literary analysis through a sustained exploration of the rise and aftermath of modernism. What was the modernist revolt of the early 20th century, how did it challenge literary tradition and existing social forms, and to what extent have we inherited a world remade by modernism? While the course will focus on British and Continental literature, writers from other parts of the world whose work closely engages the European tradition may also be considered.Authors may include Flaubert, James, Conrad, Joyce, Woolf, Kafka, Borges, Yeats, and Eliot. Instructor: Gilmartin, Gilmore.

Hum/Pl 8. Right and Wrong. *9 units (3-0-6); offered by announcement.* This course addresses questions such as: Where do our moral ideas come from? What justifies them? How should they guide our conduct, as individuals and as a society? What kind of person should one aspire to be? Topics the course may deal with include meta-ethical issues (e.g., What makes an action right or wrong? When is one morally responsible for one's actions? How should society be organized?) and normative questions (e.g., Is eating meat morally acceptable? What should we tolerate and why? What are society's obligations toward the poor?). In addition, the psychological and neural substrates of moral judgment and decision making may be explored. The course draws on a variety of sources, including selections from the great works of moral and political philosophy (e.g., Aristotle's *Nichomachean Ethics*, Hobbes's *Leviathan*, Kant's *Groundings for a Metaphysics of Morals*, and Rawls's *A Theory of Justice*), contemporary discussions of particular moral issues, and the science of moral thought. Instructors: Cowie, Quartz.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6); offered by announcement.* The theme of this course is the scope and limitations of rational belief and knowledge. Students will examine the nature of reality, the nature of the self, the nature of knowledge, and how we learn about the natural world. Students will be introduced to these issues through selections from some of the world's greatest philosophical works, including Descartes's *Meditations,* Pascal's *Pensées,* Hume's *Enquiry Concerning Human Understanding,* Berkeley's *Principles of Human Knowledge,* and Kant's *Prolegomena to any Future Metaphysics.* A variety of more contemporary readings will also be assigned. Instructors: Hitchcock, Eberhardt, Sebens.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6); offered by announcement.* Major topics include the following: What are the origins of modern Western science, when did it emerge as distinct from philosophy and other cultural and intellectual productions, and what are its distinguishing features? When and how did observation, experiment, quantification, and precision enter the practice of science? What were some of the major turning points in the history of science? What is the changing role of science and technology? Using primary and secondary sources, students will take up significant topics in the history of science, from ancient Greek science to the 20th-century revolution in physics, biology, and technology. Hum/H/HPS 10 may be taken for credit toward the additional 36-unit HSS requirement by HPS majors and minors who have already fulfilled their freshman humanities requirement and counts as a history course in satisfying the freshman humanities breadth requirement. Instructor: Feingold.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6); offered by announcement.* A consideration of the entire history of astronomy and cosmology, the oldest of all the sciences, from antiquity to the late 20th century, from the Babylonians to the Big Bang. The course will be devoted to repeating the procedures used in earlier astronomy and working directly with the primary sources. Not offered 2015–16.

F/Hum 32. Humanities on Film. *3 units (1-1-1).* For course description, see Film.

Hum 105 ab. Topics in French Culture and Literature. *9 units (3-0-6); second term.* For description, see L 105 ab.

Hum 114 abc. Spanish and Latin American Literature. *9 units (3-0-6); first, second, third terms.* For description, see L 114 abc.

Hum 119. Selected Topics in Humanities. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visitors.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); third term.* For course description, see Languages.

L/Hum 162. Spanish and Latin American Literature in Translation. *9 units (3-0-6);* For course description, see Languages.

Hum 174. Topics in Chinese Literature. *9 units (3-0-6); third term.* For description, see L 174.

INTERDISCIPLINARY STUDIES PROGRAM

Students who have chosen to enter the Interdisciplinary Studies Program (ISP) instead of a formulated undergraduate option may enroll in special ISP courses. These courses are designed to accommodate individual programs of study or special research that fall outside ordinary course offerings. The student and the instructor first prepare a written course contract specifying the work to be accomplished and the time schedule for reports on progress and for work completed. The units of credit and form of grading are decided by mutual agreement between the instructor, the student, and his or her advisory committee. See pages 275–276 for complete details.

INFORMATION SCIENCE AND TECHNOLOGY

IST 4. Information and Logic. *9 units (3-0-6); third term.* The course explains the key concepts at the foundations of computing with physical substrates, including representations of numbers, Boolean algebra as an axiomatic system, Boolean functions and their representations, composition of functions and relations, implementing functions with circuits, circuit complexity, representation of computational processes with state diagrams, state diagrams as a composition of Boolean functions and memory, and the implementation of computational processes with finite state machines. The basic concepts covered in the course are connected to advanced topics like programming, computability, logic, complexity theory, information theory, and biochemical systems. *Not offered on a pass/fail basis. Satisfies the menu requirement of the Caltech core curriculum. Freshmen only; limited enrollment.* Instructor: Bruck.

LANGUAGES

L 60 ab. German Literature in Translation. *9 units (3-0-6).* First term: *"Tales of Hollywood"*, German exile literature 1933–45; second term: German literature of the 19th century—Biedermeier, young Germany, realism, and naturalism. Not offered 2015–16.

L 102 abc. Elementary French. *9 units (3-0-6); first, second, third terms.* The course uses French in Action, a multimedia program, and emphasizes the acquisition of fundamental skills: oral ability, comprehension, writing, and reading. Students are evaluated on the basis of quizzes and compositions (1/3), midterm and final (1/3), and class participation (1/3). The course is mainly designed for students with no previous knowledge of French. Students who have had French in secondary school or college must consult with the instructor before registering. Instructor: Orcel.

L 103 abc. Intermediate French. *9 units (3-0-6); first, second, third terms. Prerequisites: L 102 abc or equivalent.* The first two terms feature an extensive grammar review and group activities that promote self- expression. Op-Ed articles and a series of literary texts provide a basis for classroom discussion and vocabulary expansion. Several short written compositions are required. The third term is designed to further develop an active command of the language. A variety of 19th- and 20th-century short stories are discussed in class to improve comprehension and oral proficiency. Students are expected to do an oral presentation, to write four short compositions, and a final paper. Instructors: Orcel, Merrill.

L 104. French Cinema. *9 units (3-0-6); first term. Offered concurrently with F 104. Prerequisites: L 103 abc or equivalent.* A critical survey of major directors, genres, and movements in French cinema. Particular attention is devoted to the development of film theory and criticism in France and their relation to film production. The course may also focus on problems of transposition from literature to cinema. The course includes screenings of films by Melies, Dulac, Clair, Renoir, Carne, Pagnol, Cocteau, Bresson, Tati, Truffaut, Godard, Resnais, Lelouch, Malle, Pialat, Rohmer, and Varda. Students are expected to write three 5-page critical papers. Conducted in French. Students who write papers in English may enroll in this class as F 104, which satisfies the advanced humanities requirement. Not offered 2015–16.

L 105 ab. Topics in French Culture and Literature. *9 units (3-0-6); second term.* Offered concurrently with Hum 105 ab. L 105 a and L 105 b taught in alternate years. Prerequisites: L 103 abc or equivalent. Part a: 20th-century French literature. Part b: Contemporary France. Conducted in French. Students who write papers in English may enroll in this class as Hum 105 ab, which satisfies the advanced humanities requirement. Instructors: Orcel.

L 106 abc. Elementary Japanese. *9 units (5-0-4); first, second, third terms. Prerequisites: Section a is required for sections b and c.* Emphasis on oral-aural skills, and understanding of basic grammar. Immediate introduction of the native script – hiragana, katakana – and gradual introduction to 300 to 500 characters. Instructor: Hirai.

L 107 abc. Intermediate Japanese. *10 units (5-1-4); first, second, third terms. Prerequisite: L 106 abc or equivalent.* Continued instruction and practice in conversation, building up vocabulary, and understanding complex sentence patterns. The emphasis, however, will be on developing reading skills. Recognition of approximately 1,000 characters. Not offered on a pass/fail basis. Instructor: Hirata.

L 108 abc. Advanced Japanese. *10 units (3-1-6); first, second, third terms. Prerequisite: L 107 abc or equivalent.* Developing overall language skills. Literary and newspaper readings. Technical and scientific translation. Improvement of listening and speaking ability so as to communicate with Japanese people in real situations. Recognition of the 1,850 "general-use characters." Not offered on a pass/fail basis. Instructor: Hirata.

L/F 109. Introduction to French Cinema from Its Beginning to the Present. *9 units (3-0-6); first term.* This course will introduce students to the artistic style and the social, historical, and political content of French films, starting with Méliès and the Lumière brothers and working through surrealism and impressionism, 1930s poetic realism, the Occupation, the New Wave, the *Cinema du look*, and the contemporary cinema. The class will teach students to look at film as a medium with its own techniques and formal principles. Conducted in English. Instructor: Orcel.

L 110 abc. Elementary Spanish. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in understanding, speaking, reading, and writing Spanish. Exclusively for students with no previous knowledge of Spanish. Instructors: Garcia, Arjona.

L 112 abc. Intermediate Spanish. *9 units (3-0-6); first, second, third terms. Prerequisite: L 110 abc or equivalent.* Grammar review, vocabulary building, practice in conversation, and introduction to relevant history, literature, and culture. Literary reading and writing are emphasized in the second and third terms. Students who have studied Spanish elsewhere must consult with the instructor before registering. Instructor: Arjona, Garcia.

L 114 abc. Spanish and Latin American Literature. *9 units (3-0-6); first, second, third terms.* Offered concurrently with Hum 114 abc. Prerequisites: L 112 abc or equivalent. First and second terms: study of literary texts from the Spanish American and Spanish traditions, their cultural and historical relevance, covering all periods, with emphasis on contemporary authors. Third term: contemporary topics in literature and/or film of the Hispanic world. Conducted in Spanish. Students who write papers in English may enroll in this class as Hum 114 abc, which satisfies the advanced humanities requirement. Instructors: Garcia, Arjona.

L 130 abc. Elementary German. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in aural comprehension, speaking, reading, and writing. Students who have had German in secondary school or college must consult with the instructor before registering. Instructor: Aebi.

L 132 abc. Intermediate German. *9 units (3-0-6); first, second, third terms. Prerequisite: L 130 abc or equivalent.* Reading of short stories and plays, grammar review, aural and oral drills and exercises, expansion of vocabulary, and practice in reading, writing, and conversational skills. Second and third terms will emphasize written expression, technical/ scientific translation, and literary readings. Students who have studied German elsewhere must consult with the instructor before registering. Instructor: Aebi.

L 140 abc. German Literature. *9 units (3-0-6). Prerequisite: L 132 c or equivalent (two years of college German), or instructor's permission.* Reading and discussion of works by selected 12th–21st-century authors, current events on Internet/TV, exposure to scientific and technical writing, business communication. Viewing and discussion of German-language films. Conducted in German. Not offered 2015–16.

H/Lit 142. Perspectives on History through Russian Literature. *9 units (3-0-6).* For course description, see History.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); third term.* First term: French classical literature of the 17th and 18th centuries; third term: reading and discussion of works by selected 19th- and 20th-century authors. The approach is both historical and critical. Conducted in English, but students may read the French originals. Film versions of the texts studied may be included. Instructors: Merrill.

L/Hum 162. Spanish and Latin American Literature in Translation. *9 units (3-0-6); offered by announcement.* This class is an introduction to the literary masterworks of the Hispanic tradition from the 16th to the 20th centuries. Readings and discussions are in English, but students may read Spanish originals.

L 167 abc. Latin Literature. *9 units (3-0-6); second, third terms. Prerequisite: three years of high-school Latin.* Major works of Latin literature, usually one per term. No work will be studied more than once in four years, and students may repeat the course for credit. Instructor: Pigman.

L 170 abc. Introduction to Chinese. *10 units (4-1-5); first, second, third terms.* An introductory course in standard Chinese (Mandarin) designed for students with no previous knowledge of the language. The course introduces the fundamentals of Chinese, including pronunciation, grammar, and Chinese characters, emphasizing the four basic language skills: listening, speaking, reading, and writing. By the end of the three-term sequence, students will have acquired knowledge of basic rules of grammar and the ability to converse, read, and write on simple topics of daily life, and will have command of more than 800 Chinese compounds and 700 characters. Instructor: Wang.

L 171 abc. Elementary Chinese. *9 units (5-0-4); first, second, third terms. Prerequisite: placement exam results or instructor's permission.* A fast-paced course for students who have had prior exposure to the language. Students are introduced to the basic principles of written and oral communication. Emphasis will be placed on consolidating basic grammar, and developing the ability to use the language creatively in talking about oneself and in dealing with daily situations within a Chinese cultural context. Instructor: Ming.

L 172 abc. Intermediate Chinese. *10 units (4-1-5); first, second, third terms. Prerequisite: L 170 abc or L 171 abc or equivalent.* A course designed to meet the personal interests and future professional goals of students who have had one year of elementary modern Chinese. Students will learn new vocabulary, sentence patterns, idiomatic expressions, and proverbs, as well as insights into Chinese society, culture, and customs. Instructor: Wang.

L 173 ab. Advanced Chinese. *10 units (3-1-6); first, second terms. Prerequisite: L 172 abc or equivalent.* A course designed to further develop overall language proficiency through extensive reading of selected texts representing a wide variety of styles and genres, including newspapers and magazines, visual materials, and a selection of works of major modern writers. Classes are conducted primarily in Chinese. Instructor: Ming.

L 174. Topics in Chinese Literature. *9 units (3-0-6); third term.* Offered concurrently with Hum 174. Prerequisites: instructor's permission. Reading and discussion of representative Chinese works from the 16th century to the present, including contemporary works from China, Taiwan, and Hong Kong. Conducted in Chinese. Students are expected to examine literary works in light of their sociopolitical and historical contexts. Students who write papers in English may enroll in this class as Hum 174, which satisfies the advanced humanities requirement. Instructors: Ming.

L 175. French Conversation. *6 units (3-0-3); third term. Prerequisites: L 102 abc and L 103 abc or equivalent.* Intense training in oral expression, pronunciation, vocabulary, listening comprehension and fluency. The class is designed for students planning to attend Ecole Polytechnique. Discussion materials and guest lectures will focus on technical language to prepare students for their classes in math and science. Taught in French. Enrollment limited to 12. L 175 can be repeated for credit since the content is never the same (different speakers, different articles discussed in class) Instructor: Orcel

H/L 191. Perspectives on History through German Literature. *9 units (3-0-6);* For course description, see History.

LAW

Law 33. Introduction to Law and Law and Economics. *9 units (3-0-6).* An introduction to Anglo-American law from both the legal and the social- scientific points of view. Subject can vary from year to year. Available for introductory social science credit. Not offered 2015–16.

Pl/Law 99. Causation and Responsibility. *9 units (3-0-6).* For course description, see Philosophy. Not offered 2015–16.

Law 134. Law and Technology. *9 units (3-0-6).* A sophisticated introduction to and exploration of the intersection of science and the law, focusing on the intellectual property system and the various means by which the conduct and products of scientific research are regulated. The course will analyze and compare American, international, and theoretical alternative systems, in part by means of economics modeling. The latter portion of the course will explore particular scientific areas in depth (examples include the human genome project; the Internet and cyberspace; the law of the sea; and outer-space exploration). Some background in law and economics helpful. Graded written work includes two problem sets, a midterm and a final using essay and short answer formats. Not offered 2015–16.

Law 135. History of Anglo-American Law. *9 units (3-0-6); second term.* An introductory survey of English law from medieval to modern times, with discussion of parallel and divergent developments in the United States. Topics include the constitution: constraints on the king, Magna Carta, the rise of parliamentary democracy, the role of courts, written versus unwritten constitutions, the U.S. Constitution; law making: statutes and the doctrine of precedent; fact finding: trial by battle and by ordeal, the development of the jury trial; civil justice: common law, equity, contract, and property law; criminal justice: private and public prosecution, star chamber, defendants' rights, criminal sanctions; family law and the changing legal status of women. Not offered 2015–16.

Law 136. Tax Law and the Democratic State. *9 units (3-0-6); second term. Prerequisites: Ec 11 or PS12.* An introduction to the role of tax in society. This course provides an overview of the U.S. tax system and the historical and political factors that influenced its development. This course will examine several key legal concepts that shape the federal income tax system as well as issues related to democracy and taxation, tax and inequality, tax and economic growth, and tax and globalization. It will also look at current tax reform proposals. Each student will be expected to complete three essays during the quarter. Not offered 2015–16.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6); second, third terms.* The development of the Supreme Court, its doctrines, personalities, and role in U.S. history through analyses of selected cases. The first half of the course, which is a prerequisite for the second half but may also be taken by itself, will deal with such topics as federalism, economic regulation, political rights, and free speech. The second half will cover such issues as the rights of the accused, equal protection, and privacy. Instructor: Kousser.

MATERIALS SCIENCE

MS 78 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised research experience, open only to senior materials science majors. Starting with an open-ended topic, students will plan and execute a project in materials science and engineering that includes written and oral reports based upon actual results, synthesizing topics from their course work. Only the first term may be taken pass/fail. Instructor: Staff.

MS 90. Materials Science Laboratory. *9 units (1-6-2); third term.* An introductory laboratory in relationships between the structure and properties of materials. Experiments involve materials processing and characterization by X-ray diffraction, scanning electron microscopy, and optical microscopy. Students will learn techniques for measuring mechanical and electrical properties of materials, as well as how to optimize these properties through microstructural and chemical control. Independent projects may be performed depending on the student's interests and abilities. Instructor: Staff.

MS 100. Advanced Work in Materials Science. The staff in materials science will arrange special courses or problems to meet the needs of students working toward the M.S. degree or of qualified undergraduate students. Graded pass/fail for research and reading. Instructor: Staff.

APh/MS 105 abc. States of Matter. *9 units (3-0-6); first, second, third terms.* For course description, see Applied Physics.

MS 110 abc. Materials Research Lectures. *1 unit; first, second, third terms.* A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructor: Staff.

MS 115. Fundamentals of Materials Science. *9 units (3-0-6); first term. Prerequisites: Ph 2.* An introduction to the structure and properties of materials and the processing routes utilized to optimize properties. All major classes of materials are covered, including metals, ceramics, electronic materials, composites, and polymers. The relationships between chemical bonding, crystal structure, thermodynamics, phase equilibria, microstructure, and properties are described. Instructors: Faber.

MS/ME/MedE 116. Mechanical Behavior of Materials. *9 units (3-0-6); second term.* Introduction to the mechanical behavior of solids, emphasizing the relationships between microstructure, defects, and mechanical properties. Elastic, anelastic, and plastic properties of crystalline and amorphous materials. Polymer and glass properties: viscoelasticity, flow, and strain-rate dependence. The relationships between stress, strain, strain rate, and temperature for deformable solids. Application of dislocation theory to strengthening mechanisms in crystalline solids. The phenomena of creep, fracture, and fatigue, and their controlling mechanisms. Instructor: Greer.

MS/APh 122. Diffraction, Imaging, and Structure. *9 units (0-4-5); second and third terms. Prerequisites: MS 132, may be taken concurrently.* Experimental methods in transmission electron microscopy of inorganic materials including diffraction, spectroscopy, conventional imaging, high resolution imaging and sample preparation. Weekly laboratory exercises to complement material in MS 132. Instructors: Staff.

MS 125. Advanced Transmission Electron Microscopy. *9 units (1-6-2); third term. Prerequisite: MS 122.* Diffraction contrast analysis of crystalline defects. Phase contrast imaging. Physical optics approach to dynamical electron diffraction and imaging. Microbeam methods for diffraction and imaging. Chemical analysis by energy dispersive X-ray spectrometry and electron energy loss spectrometry. Instructor: Ahn.

MS 131. Structure and Bonding in Materials. *9 units (3-0-6); second term. Prerequisites: graduate standing or introductory quantum mechanics.* Electronic structure and orbitals in atoms. Structure and symmetry of crystals. Reciprocal space and Brillouin zone. Born-Oppenheimer approximation. Bloch states and band theory. Tight binding and plane-waves. Lattice vibrations and lattice waves. Total energy, entropy, and Gibbs free energy in solids. Stability criteria. Bonding and electronic structure in metals, semiconductors, ionic crystals, and transition metal oxides. Point and line defects. Introduction to surfaces and amorphous materials. Instructors: Bernardi.

MS 132. Diffraction and Structure. *9 units (3-0-6); first term. Prerequisites: graduate standing or instructor's permission.* Principles of electron, X-ray, and neutron diffraction with applications to materials characterization. Imaging with electrons, and diffraction contrast of crystal defects. Kinematical theory of diffraction: effects of strain, size, disorder, and temperature. Correlation functions in solids, with introduction to space-time correlation functions. Instructors: Fultz.

MS 133. Kinetic Processes in Materials. *9 units (3-0-6); third term. Prerequisite: APh 105 b or ChE/Ch 164, or instructor's permission.* Kinetic master equation, uncorrelated and correlated random walk, diffusion. Mechanisms of diffusion and atom transport in solids, liquids, and gases. Coarsening of microstructures. Nonequilibrium processing of materials. Instructor: Greer.

MS 142. Application of Diffraction Techniques in Materials Science. *9 units (2-3-4); second term. Prerequisite: MS 120 or instructor's permission.* Applications of X-ray and neutron diffraction methods to the structural characterization of materials. Emphasis is on the analysis of polycrystalline materials but some discussion of single crystal methods is also presented. Techniques include quantitative phase analysis, crystalline size measurement, lattice parameter refinement, internal stress measurement, quantification of preferred orientation (texture) in materials, Rietveld refinement, and determination of structural features from small angle scattering. Homework assignments will focus on analysis of diffraction data. Samples of interest to students for their thesis research may be examined where appropriate. Instructor: Ahn.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6); third term. Prerequisites: MS 115 or MS 131, or instructor's permission.* Thermodynamics and kinetics of ion and electron transport in solids, with emphasis on processes in electrolyte and electrode materials used in energy storage and conversion. Treatment of electroanalytical characterization techniques including a.c. impedance spectroscopy, voltammetry, and d.c. polarization methods. Application areas include fuel cells, electrochemical gas separation membranes, batteries, supercapacitors, and hydrogen storage materials. Not offered 2015–16.

MS 150 abc. Topics in Materials Science. *Units to be arranged; first, second, third terms.* Content will vary from year to year, but will be at a level suitable for advanced undergraduate or graduate students. Topics are chosen according to the interests of students and faculty. Visiting faculty may present portions of the course. Instructor: Staff.

MS/ME 161. Imperfections in Crystals. *9 units (3-0-6); third term. Prerequisite: graduate standing or MS 115.* The relation of lattice defects to the physical and mechanical properties of crystalline solids. Introduction to point imperfections and their relationships to transport properties in metallic, covalent, and ionic crystals. Kroeger-Vink notation. Introduction to dislocations: geometric, crystallographic, elastic, and energetic properties of dislocations. Dislocation reactions and interactions including formation of locks, stacking faults, and surface effects. Relations between collective dislocation behavior and mechanical properties of crystals. Introduction to computer simulations of dislocations. Grain boundaries. The structure and properties of interfaces in solids. Emphasis on materials science aspects of role of defects in electrical, morphological, optical, and mechanical properties of solids. Not offered 2015–16.

MS/ME 166. Fracture of Brittle Solids. *9 units (3-0-6); third term. Prerequisites: MS 115a (or equivalent).* The mechanical response of brittle materials (ceramics, glasses and some network polymers) will be treated using classical elasticity, energy criteria, and fracture mechanics. The influence of environment and microstructure on mechanical behavior will be explored. Transformation toughened systems, large-grain crack-bridging systems, nanostructured ceramics, porous ceramics, anomolous glasses, and the role of residual stresses will be highlighted. Strength, flaw statistics and reliability will be discussed. Instructors: Faber.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* For course description, see Energy Science and Technology.

MS 200. Advanced Work in Materials Science. The staff in materials science will arrange special courses or problems to meet the needs of advanced graduate students.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

ME/MS 260 abc. Micromechanics. *12 units (3-0-9).* For course description, see Mechanical Engineering.

MS 300. Thesis Research.

MATHEMATICS

Ma 1 abc. Calculus of One and Several Variables and Linear Algebra. *9 units (4-0-5); first, second, third terms. Prerequisites: high-school algebra,* *trigonometry, and calculus. Special section of Ma 1 a, 12 units (5-0-7).* Review of calculus. Complex numbers, Taylor polynomials, infinite series. Comprehensive presentation of linear algebra. Derivatives of vector functions, multiple integrals, line and path integrals, theorems of Green and Stokes. Ma 1 b, c is divided into two tracks: analytic and practical. Students will be given information helping them to choose a track at the end of the fall term. There will be a special section or sections of Ma 1 a for those students who, because of their background, require more calculus than is provided in the regular Ma 1 a sequence. These students will not learn series in Ma 1 a and will be required to take Ma 1 d. Instructors: Hadian, Katz, Ramakrishnan, Graber, Ni, Flach.

Ma 1 d. Series. *5 units (2-0-3); second term only. Prerequisite: special section of Ma 1 a.* This is a course intended for those students in the special calculus-intensive sections of Ma 1 a who did not have complex numbers, Taylor polynomials, and infinite series during Ma 1 a. It may not be taken by students who have passed the regular Ma 1 a. Instructor: Staff.

Ma 2/102. Differential Equations. *9 units (4-0-5); first term. Prerequisites: Ma 1 abc.* The course is aimed at providing an introduction to the theory of ordinary differential equations, with a particular emphasis on equations with well known applications ranging from physics to population dynamics. The material covered includes some existence and uniqueness results, first order linear equations and systems, exact equations, linear equations with constant coefficients, series solutions, regular singular equations, Laplace transform, and methods for the study of nonlinear equations (equilibria, stability, predator-prey equations, periodic solutions and limiting cycles). Instructors: Makarov, Zhou.

Ma 3/103. Introduction to Probability and Statistics. *9 units (4-0-5); second term. Prerequisites: Ma 1 abc.* Randomness is not anarchy-it follows mathematical laws that we can understand and use to clarify our knowledge of the universe. This course is an introduction to the main ideas of probability and statistics. The first half is devoted to the fundamental concepts of probability theory, including distributions and random variables, independence and conditional probability, expectation, the Law of Averages (Laws of Large Numbers), and "the bell curve" (Central Limit Theorem). The second half is devoted to statistical reasoning: given our observations of the world, what can we infer about the stochastic mechanisms generating our data? Major themes include estimation of parameters (e.g. maximum likelihood), hypothesis testing, confidence intervals, and regression analysis (least squares). Students will be expected to be able to carry out computer-based analyses. Instructor: Border.

Ma 4/104. Introduction to Mathematical Chaos. *9 units (3-0-6); third term.* An introduction to the mathematics of "chaos." Period doubling universality, and related topics; interval maps, symbolic itineraries, stable/unstable manifold theorem, strange attractors, iteration of complex analytic maps, applications to multidimensional dynamics systems and real-world problems. Possibly some additional topics, such as Sarkovski's theorem, absolutely continuous invariant measures, sensitivity to initial conditions, and the horseshoe map. Instructor: Zhou.

Ma 5/105 abc. Introduction to Abstract Algebra. *9 units (3-0-6); first, second, third terms.* Introduction to groups, rings, fields, and modules. The first term is devoted to groups and includes treatments of semidirect products and Sylow's theorem. The second term discusses rings and modules and includes a proof that principal ideal domains have unique factorization and the classification of finitely generated modules over principal ideal domains. The third term covers field theory and Galois theory, plus some special topics if time permits. This course it to be taught concurrently with Ma 105. Instructors: Tsai, Mantovan, Ormerod.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisite: for Ma/CS 6 c, Ma/CS 6 a or Ma 5 a or instructor's permission.* First term: a survey emphasizing graph theory, algorithms, and applications of algebraic structures. Graphs: paths, trees, circuits, breadth-first and depth-first searches, colorings, matchings. Enumeration techniques; formal power series; combinatorial interpretations. Topics from coding and cryptography, including Hamming codes and RSA. Second term: directed graphs; networks; combinatorial optimization; linear programming. Permutation groups; counting nonisomorphic structures. Topics from extremal graph and set theory, and partially ordered sets. Third term: elements of computability theory and computational complexity. Discussion of the P=NP problem, syntax and semantics of propositional and first-order logic. Introduction to the Gödel completeness and incompleteness theorems. Instructors: Scheffer, Lupini.

Ma 7/107. Number Theory for Beginners. *9 units (3-0-6); third term.* Some of the fundamental ideas, techniques, and open problems of basic number theory will be introduced. Examples will be stressed. Topics include Euclidean algorithm, primes, Diophantine equations, including an + bn = cn and a2 - db2 = Â±1, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Ramakrishnan.

Ma 8. Problem Solving in Calculus. *3 units (3-0-0); first term. Prerequisite: simultaneous registration in Ma 1 a.* A three-hour per week hands-on class for those students in Ma 1 needing extra practice in problem solving in calculus. Instructor: Staff.

Ma 10. Oral Presentation. *3 units (2-0-1); first term. Open for credit to anyone. Freshmen must have instructor's permission to enroll.* In this course, students will receive training and practice in presenting mathematical material before an audience. In particular, students will present material of their own choosing to other members of the class. There may also be elementary lectures from members of the mathematics faculty on topics of their own research interest. Instructor: Mantovan.

Ma 11. Mathematical Writing. *3 units (0-0-3); third term. Freshmen must have instructor's permission to enroll.* Students will work with the instructor and a mentor to write and revise a self-contained paper dealing with a topic in mathematics. In the first week, an introduction to some matters of style and format will be given in a classroom setting. Some help with typesetting in TeX may be available. Students are encouraged to take advantage of the Hixon Writing Center's facilities. The mentor and the topic are to be selected in consultation with the instructor. It is expected that in most cases the paper will be in the style of a textbook or journal article, at the level of the student's peers (mathematics students at Caltech). *Fulfills the Institute scientific writing requirement.* Not offered on a pass/fail basis. Instructor: Graber.

FS/Ma 12. The Mathematics of Enzyme Kinetics. *2-0-4; third term. Prerequisites: Ma 1a, b.* For course description, see Freshman Seminar. Not offered 2015–16.

Ma 17. How to Solve It. *4 units (2-0-2); first term.* There are many problems in elementary mathematics that require ingenuity for their solution. This is a seminar-type course on problem solving in areas of mathematics where little theoretical knowledge is required. Students will work on problems taken from diverse areas of mathematics; there is no prerequisite and the course is open to freshmen. May be repeated for credit. Graded pass/fail. Instructor: Katz.

Ma 20. Frontiers in Mathematics. *1-0-0; first term. Prerequisites: Open for credit to freshman and sophomores.* Weekly seminar by a member of the math department or a visitor, to discuss his or her research at an introductory level. The course aims to introduce students to research areas in mathematics and help them gain an understanding of the scope of the field. Graded pass/fail. Instructors: Katz.

Ma 92 abc. Senior Thesis. *9 units (0-0-9); first, second, third terms. Prerequisites: To register, the student must obtain permission of the mathematics undergraduate representative.* Open only to senior mathematics majors who are qualified to pursue independent reading and research. This research must be supervised by a faculty member. The research must begin in the first term of the senior year and will normally follow up on an earlier SURF or independent reading project. Two short presentations to a thesis committee are required: the first at the end of the first term and the second at the midterm week of the third term. A draft of the written thesis must be completed and distributed to the committee one week before the second presentation. Graded pass/fail in the first and second terms; a letter grade will be given in the third term.

Ma 98. Independent Reading. *3–6 units by arrangement.* Occasionally a reading course will be offered after student consultation with a potential supervisor. Topics, hours, and units by arrangement. Graded pass/fail.

Ma 106. Elliptic Curves. *9 units (3-0-6); third term. Prerequisites: Ma 5 or equivalent.* The ubiquitous elliptic curves will be analyzed from elementary, geometric, and arithmetic points of view. Possible topics are the group structure via the chord-and-tangent method, the Nagel-Lutz procedure for finding division points, Mordell's theorem on the finite generation of rational points, points over finite fields through a special case treated by Gauss, Lenstra's factoring algorithm, integral points. Other topics may include diophantine approximation and complex multiplication. Not offered 2015–16.

Ma 108 abc. Classical Analysis. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 or equivalent, or instructor's permission.* May be taken concurrently with Ma 109. First term: structure of the real numbers, topology of metric spaces, a rigorous approach to differentiation in R^n. Second term: brief introduction to ordinary differential equations; Lebesgue integration and an introduction to Fourier analysis. Third term: the theory of functions of one complex variable. Instructors: Frank, Katz, Demerel.

Ma 109 abc. Introduction to Geometry and Topology. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 or equivalent, and Ma 108 must be taken previously or concurrently.* First term: aspects of point set topology, and an introduction to geometric and algebraic methods in topology. Second term: the differential geometry of curves and surfaces in two- and three-dimensional Euclidean space. Third term: an introduction to differentiable manifolds. Transversality, differential forms, and further related topics. Instructors: Vafaee, Zhang, Markovic.

Ma 110 abc. Analysis. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 108 or previous exposure to metric space topology, Lebesgue measure.* First term: integration theory and basic real analysis: topological spaces, Hilbert space basics, Fejer's theorem, measure theory, measures as functionals, product measures, L^p -spaces, Baire category, Hahn- Banach theorem, Alaoglu's theorem, Krein-Millman theorem, countably normed spaces, tempered distributions and the Fourier transform. Second term: basic complex analysis: analytic functions, conformal maps and fractional linear transformations, idea of Riemann surfaces, elementary and some special functions, infinite sums and products, entire and meromorphic functions, elliptic functions. Third term: harmonic analysis; operator theory. Harmonic analysis: maximal functions and the Hardy-Littlewood maximal theorem, the maximal and Birkoff ergodic theorems, harmonic and subharmonic functions, theory of H^p -spaces and boundary values of analytic functions. Operator theory: compact operators, trace and determinant on a Hilbert space, orthogonal polynomials, the spectral theorem for bounded operators. If time allows, the theory of commutative Banach algebras. Instructors: Silva, Rains, Markovic.

Ma 111 ab. Topics in Analysis. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 110 or instructor's permission.* This course will discuss advanced topics in analysis, which vary from year to year. Topics from previous years include potential theory, bounded analytic functions in the unit disk, probabilistic and combinatorial methods in analysis, operator theory, C*-algebras, functional analysis. The third term will cover special functions: gamma functions, hypergeometric functions, beta/Selberg integrals and q-analogues. Time permitting: orthogonal polynomials, Painlev\'e transcendents and/or elliptic analogues Instructors: Frank, Fathizadeh, Silva.

Ma 112 ab. Statistics. *9 units (3-0-6); second term. Prerequisite: Ma 2 a probability and statistics or equivalent.* The first term covers general methods of testing hypotheses and constructing confidence sets, including regression analysis, analysis of variance, and nonparametric methods. The second term covers permutation methods and the bootstrap, point estimation, Bayes methods, and multistage sampling. Not offered 2015–16.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 5 or equivalent, or instructor's permission.* First term: Introduction to first-order logic and model theory. The Godel Completeness Theorem and the Completeness Theorem. Definability, elementary equivalence, complete theories, categoricity. The Skolem-Lowenheim Theorems. The back and forth method and Ehrenfeucht-Fraisse games. Farisse theory. Elimination of quantifiers, applications to algebra and further related topics if time permits. Second and third terms: Axiomatic set theory, ordinals and cardinals, the Axiom of Choice and the Continuum Hypothesis. Models of set theory, independence and consistency results. Topics in descriptive set theory, combinatorial set theory and large cardinals. Instructor: Kechris.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or instructor's permission.* Various approaches to computability theory, e.g., Turing machines, recursive functions, Markov algorithms; proof of their equivalence. Church's thesis. Theory of computable functions and effectively enumerable sets. Decision problems. Undecidable problems: word problems for groups, solvability of Diophantine equations (Hilbert's 10th problem). Relations with mathematical logic and the Gödel incompleteness theorems. Decidable problems, from number theory, algebra, combinatorics, and logic. Complexity of decision procedures. Inherently complex problems of exponential and superexponential difficulty. Feasible (polynomial time) computations. Polynomial deterministic vs. nondeterministic algorithms, NP-complete problems and the P = NP question. Not offered 2015–16.

Ma 118. Topics in Mathematical Logic: Geometrical Paradoxes. *9 units (3-0-6); second term. Prerequisite: Ma 5 or equivalent, or instructor's permission.* This course will provide an introduction to the striking paradoxes that challenge our geometrical intuition. Topics to be discussed include geometrical transformations, especially rigid motions; free groups; amenable groups; group actions; equidecomposability and invariant measures; Tarski's theorem; the role of the axiom of choice; old and new paradoxes, including the Banach-Tarski paradox, the Laczkovich paradox (solving the Tarski circle-squaring problem), and the Dougherty-Foreman paradox (the solution of the Marczewski problem). Not offered 2015–16.

Ma 120 abc. Abstract Algebra. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 5 or equivalent or instructor's permission.* This course will discuss advanced topics in algebra. Among them: an introduction to commutative algebra and homological algebra, infinite Galois theory, Kummer theory, Brauer groups, semisimiple algebras, Weddburn theorems, Jacobson radicals, representation theory of finite groups. Instructors: Solis, Rains, Tsai.

Ma 121 ab. Combinatorial Analysis. *9 units (3-0-6); first, second, terms. Prerequisite: Ma 5.* A survey of modern combinatorial mathematics, starting with an introduction to graph theory and extremal problems. Flows in networks with combinatorial applications. Counting, recursion, and generating functions. Theory of partitions. (0, 1)-matrices. Partially ordered sets. Latin squares, finite geometries, combinatorial designs, and codes. Algebraic graph theory, graph embedding, and coloring. Instructors: Omerod, Katz.

Ma 123. Classification of Simple Lie Algebras. *9 units (3-0-6); third term. Prerequisite: Ma 5 or equivalent.* This course is an introduction to Lie algebras and the classification of the simple Lie algebras over the complex numbers. This will include Lie's theorem, Engel's theorem, the solvable radical, and the Cartan Killing trace form. The classification of simple Lie algebras proceeds in terms of the associated reflection groups and a classification of them in terms of their Dynkin diagrams. Not offered 2015–2016.

Math 125. Algebraic Curves. *8 units (3-0-6). Prerequisites: Ma 5.* An elementary introduction to the theory of algebraic curves. Topics to be covered will include affine and projective curves, smoothness and singularities, function fields, linear series, and the Riemann-Roch theorem. Possible additional topics would include Riemann surfaces, branched coverings and monodromy, arithmetic questions, introduction to moduli of curves. Not offered 2015–16.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2.* For course description, see Electrical Engineering.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

Ma 130 abc. Algebraic Geometry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 120 (or Ma 5 plus additional reading).* Plane curves, rational functions, affine and projective varieties, products, local properties, birational maps, divisors, differentials, intersection numbers, schemes, sheaves, general varieties, vector bundles, coherent sheaves, curves and surfaces. Instructor: Solis, Graber, Ramakrishnan.

Ma 132 c. Topics in Algebraic Geometry. *9 units (3-0-6); third term. Prerequisites: Ma 130 or instructor's permission.* This course will cover advanced topics in algebraic geometry that will vary from year to year. This year, the topic will be deformation theory. Not offered 2015–16.

Ma 135 ab. Arithmetic Geometry. *9 units (3-0-6); first, second terms. Prerequisite: Ma 130.* The course deals with aspects of algebraic geometry that have been found useful for number theoretic applications. Topics will be chosen from the following: general cohomology theories (étale cohomology, flat cohomology, motivic cohomology, or p-adic Hodge theory), curves and Abelian varieties over arithmetic schemes, moduli spaces, Diophantine geometry, algebraic cycles. Not offered 2015–16.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6); second term. Prerequisite: Ma 108; Ma 109 is desirable.* The mathematical theory of ordinary and partial differential equations, including a discussion of elliptic regularity, maximal principles, solubility of equations. The method of characteristics. Instructor: Frank.

Ma/ACM 144 ab. Probability. *9 units (3-0-6); first, second terms. Prerequisites: For 144a, Ma 108b is strongly recommended; for 144b, 108b and 144a are prerequisite.* Overview of measure theory. Random walks and the Strong law of large numbers via the theory of martingales and Markov chains. Characteristic functions and the central limit theorem. Poisson process and Brownian motion. Topics in statistics. Instructors: Makarov, Fathizadeh.

Ma 145 a. Representation Theory. *9 units (3-0-6); first term. Prerequisites: For 145a Ma 5 is a prerequisite; for 145b, Ma 108ab are strongly recommended.* The study of representations of a group by unitary operators on a Hilbert space, including finite and compact groups, and, to the extent that time allows, other groups. First term: general representation theory of finite groups. Frobenius's theory of representations of semidirect products. The Young tableaux and the representations of symmetric groups. Second term: the Peter-Weyl theorem. The classical compact groups and their representation theory. Weyl character formula. Instructors: Rains

Ma 147 abc. Dynamical Systems. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 108, Ma 109, or equivalent.* First term: real dynamics and ergodic theory. Second term: Hamiltonian dynamics. Third term: complex dynamics. Not offered 2015–16.

Ma 148 ab. Topics in Mathematical Physics. *9 units (3-0-6); second, third terms.* This course covers a range of topics in mathematical physics. The content will vary from year to year. Topics covered will include some of the following: Lagrangian and Hamiltonian formalism of classical mechanics; mathematical aspects of quantum mechanics: Schroedinger equation, spectral theory of unbounded operators, representation theoretic aspects; partial differential equations of mathematical physics (wave, heat, Maxwell, etc.); rigorous results in classical and/or quantum statistical mechanics; mathematical aspects of quantum field theory; general relativity for mathematicians. First term: geometric theory of quantum information and quantum entanglement based on information geometry and entropy. Instructor: Marcolli.

Ma 151 abc. Algebraic and Differential Topology. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 109 abc or equivalent.* A basic graduate core course. Fundamental groups and covering spaces, homology and calculation of homology groups, exact sequences. Fibrations, higher homotopy groups, and exact sequences of fibrations. Bundles, Eilenberg-Maclane spaces, classifying spaces. Structure of differentiable manifolds, transversality, degree theory, De Rham cohomology, spectral sequences. Instructors: Vafaee, Ni.

Ma 157 ab. Riemannian Geometry. *9 units (3-0-6); second, third terms. Prerequisite: Ma 151 or equivalent, or instructor's permission.* Part a: basic Riemannian geometry: geometry of Riemannian manifolds, connections, curvature, Bianchi identities, completeness, geodesics, exponential map, Gauss's lemma, Jacobi fields, Lie groups, principal bundles, and characteristic classes. Part b: basic topics may vary from year to year and may include elements of Morse theory and the calculus of variations, locally symmetric spaces, special geometry, comparison theorems, relation between curvature and topology, metric functionals and flows, geometry in low dimensions. Instructors: Trnkova, Zhang.

Ma 160 abc. Number Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5.* In this course, the basic structures and results of algebraic number theory will be systematically introduced. Topics covered will include the theory of ideals/divisors in Dedekind domains, Dirichlet unit theorem and the class group, p-adic fields, ramification, Abelian extensions of local and global fields. Instructors: Flach, Mantovan.

Ma 162 ab. Topics in Number Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ma 160.* The course will discuss in detail some advanced topics in number theory, selected from the following: Galois representations, elliptic curves, modular forms, L-functions, special values, automorphic representations, p-adic theories, theta functions, regulators. Not offered 2015–16.

Ma 191 abc. Selected Topics in Mathematics. *9 units (3-0-6); first, second, third terms.* Each term we expect to give between 0 and 6 (most often 2-3) topics courses in advanced mathematics covering an area of current research interest. These courses will be given as sections of 191. Students may register for this course multiple times even for multiple sections in a single term. The topics and instructors for each term and course descriptions will be listed on the math option website each term prior to the start of registration for that term. Instructor: Staff.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6); first term.* For course description, see Social Science.

Ma 290. Reading. *Hours and units by arrangement.* Occasionally, advanced work is given through a reading course under the direction of an instructor.

Ma 390. Research. *Units by arrangement.*

See also the list of courses in Applied and Computational Mathematics.

MECHANICAL ENGINEERING

Additional advanced courses in the field of mechanical engineering may be found listed in other engineering options such as aerospace engineering, applied mechanics, applied physics, control and dynamical systems, and materials science.

EE/ME 7. Introduction to Mechatronics. *6 units (2-3-1).* For course description, see Electrical Engineering.

ME 8. Thinking Like an Engineer. *6 units (3-0-3); second term.* An introduction to principles and techniques useful for Mechanical Engineering. Units and dimensional analysis; order-of-magnitude estimation; prototyping and model-scale experiments; visualization and computer-aided design. Case studies will be presented by weekly guest lecturers by practicing engineers in industry and academia. Not offered 2015–16.

ME 11 abc. Thermal Science. *9 units (3-0-6); first, second, third terms. Prerequisites: Sophomore standing required; ME 12 abc, may be taken concurrently.* An introduction to classical thermodynamics and transport with engineering applications. First and second laws; closed and open systems; properties of a pure substance; availability and irreversibility; generalized thermodynamic relations; gas and vapor power cycles; propulsion; mixtures; combustion and thermochemistry; chemical equilibrium; momentum and heat transfer including boundary layers with applications to internal and external flows. Not offered on a pass/fail basis. Instructors: Hunt, Blanquart.

ME 12 abc. Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Sophomore standing required; ME 11 abc, may be taken concurrently.* An introduction to statics and dynamics of rigid bodies, deformable bodies, and fluids. Equilibrium of force systems, principle of virtual work, distributed force systems, friction, static analysis of rigid and deformable structures, hydrostatics, kinematics, particle dynamics, rigid-body dynamics, Euler's equations, ideal flow, vorticity, viscous stresses in fluids, dynamics of deformable systems, waves in fluids and solids. Not offered on a pass/fail basis. Instructors: Mello, Andrade.

ME 13/130. Introduction to Mechanical Prototyping. *4 units (0-4-0); first, second, summer terms.* Enrollment is limited and is based on responses to a questionnaire available in the Registrar's Office during registration. Introduction to the technologies and practices needed to fabricate mechanical prototypes. Students will acquire the fundamental skills necessary to begin using 3D Computer Aided Design Software. Students will learn how to build parametric models of parts and assemblies and learn how to generate detailed drawings of their designs. Students will also be introduced to both manual and computer-aided machining techniques, as well as computer-controlled prototyping technologies, such as three-dimensional printing, laser cutting, and water jet cutting. Students will receive safety-training, instruction on the theories underlying different machining methods, and hands-on demonstrations of machining and mechanical assembly methods.

Several prototypes will be constructed using the various technologies available in the mechanical engineering machine shop. Instructors: Van Deusen.

ME 14. Design and Fabrication. *9 units (3-5-1); third term. Prerequisites: ME 12ab, ME 13. Enrollment is limited and will be based on responses to a questionnaire available in the Registrar's office.* Introduction to mechanical engineering design, fabrication, and visual communication. Concepts are taught through a series of short design projects and design competitions emphasizing physical concepts. Many class projects will involve substantial use of the shop facilities, and construction of working prototypes. Not offered on a pass/fail basis. Instructors: Mello, Van Deusen.

ME 50 ab. Experiments and Modeling in Mechanical Engineering. *9 units (0-6-3); second, third terms. Prerequisites: ME 11 abc, ME 12 abc, ME 13, ME 14, and programming skills at the level of CS 1 and ACM 11.* Laboratory experiments and modeling of systems relevant to Mechanical Engineering. First offered 2015-2016. Instructors: Hall, Blanquart, Mello.

ME 65. Mechanics of Materials. *9 units (3-0-6); first term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to continuum mechanics, principles of elasticity, plane stress, plane strain, axisymmetric problems, stress concentrations, thin films, fracture mechanics, variational principles, frame structures, finite element methods, composites, and plasticity. Taught concurrently with Ae/AM/CE/ME 102. Not offered 2015–16.

ME 66. Vibration. *9 units (3-0-6); first term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to vibration and wave propagation in continuous and discrete multi-degree-of-freedom systems. Strings, mass-spring systems, mechanical devices, elastic continua. Equations of motion, Lagrange's equations, Hamilton's principle, and time-integration schemes. Taught concurrently with AM/CE 151 a. Instructor: Heaton.

ME 72 ab. Engineering Design Laboratory. *9 units (3-4-2) first term; (1-8-0) second term; first, second terms. Prerequisites: ME 14. Enrollment is limited.* Enrollment is limited. A project-based course in which teams of students design, fabricate, analyze, test, and operate an electromechanical device to compete against devices designed by other student teams. The class lectures and the projects stress the integration of mechanical design, sensing, engineering analysis, and computation to solve problems in engineering system design. The laboratory units of ME 72 can be used to fulfill a portion of the laboratory requirement for the ME or EAS option. Not offered on a pass/fail basis. Instructors: Mello, Van Duesen.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or 18 units (2-15-1) third term.* For course description, see Computer Science.

ME 90 abc. Senior Thesis, Experimental. *9 units; (0-0-9) first term; (0-9-0) second, third terms. Prerequisites: senior status; instructor's permission.* Experimental research supervised by an engineering faculty member. The topic selection is determined by the adviser and the student and is subject to approval by the Mechanical Engineering Undergraduate Committee. First and second terms: midterm progress report and oral presentation during finals week. Third term: completion of thesis and final presentation. The second and third terms may be used to fulfill laboratory credit for EAS. Not offered on a pass/fail basis. Instructor: Blanquart.

ME 96. Mechanical Engineering Laboratory. *9 units (0-9-0); third term. Prerequisites: ME 18 ab, ME 19 ab, ME 35 ab.* A laboratory course with experiments drawn from diverse areas of mechanical engineering, including heat transfer, control, fluid mechanics, solid mechanics, atomic force microscopy, materials, combustion, turbomachinery, and dynamics. Taught concurrently with ME 50 b. Not offered after 2015–2016.

ME 100. Independent Studies in Mechanical Engineering. *Units are assigned in accordance with work accomplished.* A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of undergraduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aerospace.

E/ME 103. Management of Technology. *9 units (3-0-6).* For course description, see Engineering.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); second, third terms.* For course description, see Engineering.

EST/EE/ME 109. Energy Technology and Policy. *9 units (3-0-6); first term.* For course description, see Energy Science and Technology.

ME 110. Special Laboratory Work in Mechanical Engineering. *3–9 units per term; maximum two terms.* Special laboratory work or experimental research projects may be arranged by members of the faculty to meet the needs of individual students as appropriate. A written report is required for each term of work. Instructor: Staff.

CE/ME 112 ab. Hydraulic Engineering. *9 units (3-0-6).* For course description, see Civil Engineering.

ME 115 ab. Introduction to Kinematics and Robotics. *9 units (3-0-6); second, third terms. Prerequisites: Ma 2, ACM 95/100 ab recommended.* Introduction to the study of planar, rotational, and spatial motions with applications to robotics, computers, computer graphics, and mechanics. Topics in kinematic analysis will include screw theory, rotational representations, matrix groups, and Lie algebras. Applications include robot kinematics, mobility in mechanisms, and kinematics of open and closed chain mechanisms. Additional topics in robotics include path planning for robot manipulators, dynamics and control, and assembly. Course work will include laboratory demonstrations using simple robot manipulators. Instructor: Burdick.

MS/ME/MedE 116. Mechanical Behavior of Materials. *9 units (3-0-6); second term.* For course description, see Materials Science.

ME 117. Nano-to-Macro Transport Processes. *9 units (3-0-6); second term. Prerequisites: ME 11 abc, ME 12 abc, ACM 95 or equivalent.* This course provides a parallel treatment of photons, electrons, phonons, and molecules as energy carriers, aiming at fundamental understanding and descriptive tools for energy and heat transport processes from the nanoscale continuously to the macroscale. Topics include energy transport in the form of waves and particles, scattering and heat generation processes, Boltzmann equation and derivation of classical laws, deviation from classical laws at the nanoscale and their appropriate descriptions, with applications in nano- and microtechnology. Not offered 2015–16.

Ae/ME 118. Classical Thermodynamics. *9 units (3-0-6); first term.* For course description, see Aerospace.

ME 119 ab. Heat and Mass Transfer. *9 units (3-0-6); first, second terms. Prerequisites: ME 11 abc, ME 12 abc, ACM 95/100 (may be taken concurrently).* Transport properties, conservation equations, conduction heat transfer, convective heat and mass transport in laminar and turbulent flows, phase change processes, thermal radiation. Instructor: Minnich

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6).* For course description, see Aerospace.

ME 131. Advanced Robotics: Manipulation and Sensing. *9 units (3-6-0); third term. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of robotic manipulation and sensing. Past topics have included advanced manipulator kinematics, grasping and dextrous manipulation using multifingered hands, and advanced obstacle avoidance and motion planning algorithms. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Not offered 2015–16.

ME/CS 132 ab. Advanced Robotics: Navigation and Vision. *9 units (3-6-0); second, third terms. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of autonomous navigation and vision. Topics will include mobile robots, multilegged walking machines, use of vision in navigation systems. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Not offered 2015–16.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term.* For course description, see Applied Mechanics.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aerospace.

MS/ME 161. Imperfections in Crystals. *9 units (3-0-6).* For course description, see Materials Science.

ME/CE 163. Mechanics and Rheology of Fluid-Infiltrated Porous Media. *9 units (3-0-6); second term. Prerequisites: Continuum Mechanics - Ae/Ge/ME 160 ab.* This course will focus on the physics of porous materials (e.g., geomaterials, biological tissue) and their intimate interaction with interstitial fluids (e.g., water, oil, blood). The course will be split into two parts: Part 1 will focus on the continuum mechanics (balance laws) of multi-phase solids, with particular attention to fluid diffusion-solid deformation coupling. Part 2 will introduce the concept of effective stresses and state of the art rheology available in modeling the constitutive response of representative porous materials. Emphasis will be placed on poro-elasticity and poro-plasticity. Instructor: Andrade.

AM/ME 165 ab. Elasticity. *9 units (3-0-6).* For course description, see Applied Mechanics.

MS/ME 166. Fracture of Brittle Solids. *9 units (3-0-6); third term.* For course description, see Materials Science.

CE/ME/Ge 173. Mechanics of Soils. *9 units (3-0-6); second term.* For course description, see Civil Engineering.

ME/CE/Ge 174. Mechanics of Rocks. *9 units (3-0-6); third term. Prerequisites: Ae/Ge/ME 160a.* Basic principles of deformation, strength, and stressing of rocks. Elastic behavior, plasticity, viscoelasticity, viscoplasticity, creep, damage, friction, failure mechanisms, shear localization, and interaction of deformation processes with fluids. Engineering and geological applications. Instructors: Lapusta.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* For course description, see Energy Science and Technology.

ME 200. Advanced Work in Mechanical Engineering. A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

ME 201. Advanced Topics in Mechanical Engineering. *9 units (3-0-6).* The faculty will prepare courses on advanced topics to meet the needs of graduate students.

ME 202 abc. Engineering Two-Phase Flows. *9 units (3-0-6). Prerequisites: ACM 95/100 ab, Ae/APh/CE/ME 101 abc, or equivalents.* Selected topics in engineering two-phase flows with emphasis on practical problems in modern hydro-systems. Fundamental fluid mechanics and heat, mass, and energy transport in multiphase flows. Liquid/vapor/gas (LVG) flows, nucleation, bubble dynamics, cavitating and boiling flows, models of LVG flows; instabilities, dynamics, and wave propagation; fluid/structure interactions. Discussion of two-phase flow problems in conventional, nuclear, and geothermal power plants, marine hydrofoils, and other hydraulic systems. Not offered 2015–16.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

Ae/ME 218. Statistical Mechanics. *3-0-6; second term.* For course description, see Aerospace.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. *6 units (2-0-4); third term.* For course description, see Civil Engineering.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. *9 units; (3-0-6 a, 1-3-5- b).* For course description, see Aerospace.

ME/MS 260 ab. Micromechanics. *12 units (3-0-9); second, third terms. Prerequisites: ACM 95/100 or equivalent, and Ae/AM/CE/ME 102 abc or Ae 160 abc or instructor's permission.* The course gives a broad overview of micromechanics, emphasizing the microstructure of materials, its connection to molecular structure, and its consequences on macroscopic properties. Topics include phase transformations in crystalline solids, including martensitic, ferroelectric, and diffusional phase transformations, twinning and domain patterns, active materials; effective properties of composites and polycrystals, linear and nonlinear homogenization; defects, including dislocations, surface steps, and domain walls; thin films, asymptotic methods, morphological instabilities, self-organization; selected applications to microactuation, thin-film processing, composite materials, mechanical properties, and materials design. Open to undergraduates with instructor's permission. Not offered 2015–16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6); second, third terms. Prerequisites: Ae/AM/CE/ME 102 abc or Ae/Ge/ME 160 ab or instructor's permission.* Introduction to elastodynamics and waves in solids. Dynamic fracture theory, energy concepts, cohesive zone models. Friction laws, nucleation of frictional instabilities, dynamic rupture of frictional interfaces. Radiation from moving cracks. Thermal effects during dynamic fracture and faulting. Crack branching and faulting along nonplanar interfaces. Related dynamic phenomena, such as adiabatic shear localization. Applications to engineering phenomena and physics and mechanics of earthquakes. Not offered 2015–16.

ME 300. Research in Mechanical Engineering. *Hours and units by arrangement.* Research in the field of mechanical engineering. By arrangement with members of the faculty, properly qualified graduate students are directed in research.

MEDICAL ENGINEERING

MedE 99. Undergraduate Research in Medical Engineering. *Variable units as arranged with the advising faculty member; first, second, third terms.* Undergraduate research with a written report at the end of each term; supervised by a Caltech faculty member, or co-advised by a Caltech faculty member and an external researcher. Graded pass/fail. Instructor: Staff.

MedE 100 abc. Medical Engineering Seminar. *1 unit; first, second, third terms.* All PhD degree candidates in Medical Engineering are required to attend all MedE seminars. If there is no MedE seminar during a week, then the students should go to any other graduate-level seminar that week. Students should broaden their knowledge of the engineering principles and sciences of medical engineering. Students are expected to learn the forefronts of the research and development of medical materials, technologies, devices and systems from the seminars. Graded pass/fail. Instructor: Choo.

MedE 101. Introduction to Clinical Physiology and Pathophysiology for Engineers. *9 units, 3-0-6; First term. Prerequisites: No Prerequisites, Bi 1 or equivalent recommended.* The goal of this course is to introduce engineering scientists to medical physiological systems: with a special emphasis on the clinical relevance. The design of the course is to present two related lectures each week in a case study format: An overview of the physiology of a system followed by examples of pathophysiology as well as diagnostic and therapeutic modalities. The Final two weeks of the course will be a mini-work shop where the class explores challenging problems in medical physiology. The course ultimately seeks to promote a bridge between relevant clinical problems and engineering scientists who desire to solve them. Graded pass/fail. Instructor: Petrasek.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6).* For course decription, see Engineering.

BE/Bi/MedE 106. Introduction to Biomechanics. *9 units (3-0-6).* For course description, see Bioengineering.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6).* For course description, see Chemical Engineering.

EE/MedE 114ab. Analog Circuits Design. *12 units (4-0-8); second and third term.* For course description, see Electrical Engineering.

EE/MedE 115. Micro-/Nano-scales Electro-optics. *9 units (3-0-6); first term.* For course description, see Electrical Engineering.

MS/ME/MedE 116. Mechanical Behavior of Materials. *9 units (3-0-6).* For course description, see Materials Science.

EE/MedE 124. Mixed-mode Integrated Circuits. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

EE/BE/MedE 166. Optical Methods for Biomedical Imaging and Diagnostics. *9 units (3-1-5); third term.* For course description, see Electrical Engineering.

EE/BE/MedE 185. MEMS Technology and Devices. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

EE/MedE 187. VLSI and ULSI Technology. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

ChE/BE/MedE 188. Molecular Imaging. *9 units (3-0-6).* For course description see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. *12 units (3-6-3) a; 9 units (0-9-0) b.* For course description, see Bioengineering.

MedE 199. Special Topics in Medical Engineering. *Units to be arranged, terms to be arranged.* Subject matter will change from term to term depending upon staff and student interest, but will generally center on the understanding and applying engineering for medical problems. Instructor: Staff.

MedE 201ab. Principles and Design of Medical Devices. *9 units (3-0-6); second and third term***.** *Prerequisite: instructor's permission.* This course provides a broad coverage on the frontiers of medical diagnostic and therapeutic technologies and devices based on multidisciplinary engineering principles. Topics include biomaterials and biomechanics; micro/nanofluidics; micro/nano biophotonics and medical imaging; medical electronics, wireless communications through the skin and tissue; electrograms and biotic/abiotic interface; biochips, microPCR and sequencer and biosensors; micro/nano implants. The course will focus on the scientific fundamentals specific to medical applications. However, both the lectures and assignments will also emphasize the design aspects of the topics as well as up-to-date literature study. Instructors: Tai, Choo.

MedE 205. New Frontiers in Medical Technologies. *6 units, (2-0-4); third term. Prerequisites: None but knowledge of semiconductor physics and some system engineering, basic electrical engineering highly recommended.* New Frontiers of Medical Technologies is an introductory graduate level course that describes space technologies, instruments, and engineering techniques with current and potential applications in medicine. The main thrust of these medical engineering elements development has been toward space exploration. Spinoff applications to medicine has been explored and proven with various degrees of success and maturity. This class introduces these topics, their intended original space applications and the medical applications. Topics include but not limited to multimodal imaging, UV/Visible/NIR imaging, imaging spectrometry, sensors, robotics, and navigation. Instructor: Shouleh Nikzad.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6); second term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Internal flows: steady and pulsatile blood flow in compliant vessels, internal flows in organisms. Fluid dynamics of the human circulatory system: heart, veins, and arteries (microcirculation). Mass and momentum transport across membranes and endothelial layers. Fluid mechanics of the respiratory system. Renal circulation and circulatory system. Biological pumps. Instructor: Pahlevan.

MedE 291. Research in Medical Engineering. *Units to be arranged, first, second, third terms.* Qualified graduate students are advised in medical engineering research, with the arrangement of MedE staff.

MUSIC

Mu 21. Understanding Music. *9 units (3-0-6); first term.* The Listening Experience I. How to listen to and what to listen for in classical and other musical expressions. Listening, analysis, and discussion of musical forms, genres, and styles. Course is intended for musicians as well as nonmusicians and is strongly recommended as an introduction to other music courses. Instructor: Neenan.

Mu 24. Introduction to Opera. *9 units (3-0-6); third term.* Opera exploded onto the cultural scene around the year 1600 and quickly became the most popular, expensive, and lavish spectacle in all of Europe. The course will trace the history of the genre examining masterpieces by Monteverdi, Handel, Mozart, Rossini, Verdi, Wagner, Strauss, Berg, and Britten, and will sample a host of newer works, including *Einstein on the Beach, The Death of Klinghoffer,* and *The Ghosts of Versailles.* Not offered 2015–16.

Mu 25. History of Chamber Music. *9 units (3-0-6); third term.* To be coordinated with Caltech's spring chamber music performances; enrollment limited to students preparing performances of chamber music during the term. The course will survey the history of chamber music and will offer more in-depth exploration of works in preparation for performance. Not offered 2015–16.

Mu 26. Jazz History. *9 units (3-0-6); third term.* This course will examine the history of jazz in America from its roots in the unique confluence of racial and ethnic groups in New Orleans around 1900 to the present. The lives and music of major figures such as Robert Johnson, Jelly Roll Morton, Louis Armstrong, Benny Goodman, Duke Ellington, Count Basie, Charlie Parker, Dizzy Gillespie, Thelonius Monk, Miles Davis and others will be explored. Not offered 2015–16.

Mu 27. Fundamentals of Music Theory and Elementary Ear Training. *9 units (3-0-6); first term.* Basic vocabulary and concepts of music theory (rhythm and pitch notation, intervals, scales, function of key signatures, etc.); development of aural perception via elementary rhythmic and melodic dictation, and sight-singing exercises. Instructor: Neenan.

Mu 28. Harmony I. *9 units (3-0-6), second term. Prerequisite: Mu 27 or entrance exam.* Study of tonal harmony and intermediate music theory; techniques of chord progression, modulation, and melody writing according to common practice; ear training, continued. Instructor: Neenan.

Mu 29. Harmony II. *9 units (3-0-6), third term. Prerequisite: Mu 28 or entrance exam.* More advanced concepts of music theory, including chromatic harmony, and 20th-century procedures relating to selected popular music styles; ear training, continued. Instructor: Neenan.

Mu 122. Life and Music of Mozart. *9 units (3-0-6); second term.* This course will explore Mozart's music within the context of his life and times, including the early works composed as a child prodigy and touring artist; the first masterpieces he composed, and finally the masterworks written during his meteoric rise and his equally amazing fall from grace. Not offered 2015–16.

Mu 123. Life and Music of Beethoven. *9 units (3-0-6); third term.* The course will examine the exuberant works of Beethoven's youth, the series of grand, heroic masterpieces of the early 1800s, and the puzzling and mysterious works of his final decade. Not offered 2015–16.

Mu 137. History I: Music History to 1750. *9 units (3-0-6); first term.* The course traces the history of music from ancient Greece to the time of Bach and Handel. A survey of the contributions by composers such as Machaut, Josquin, and Palestrina will lead to a more in-depth look at the music of Monteverdi, Purcell, Corelli, Vivaldi, and the two most important composers of the high baroque, Bach and Handel. Not offered 2015–16.

Mu 138. History II: Music History from 1750 to 1850. *9 units (3-0-6); second term.* Music composed between 1750 and 1850 is among the most popular concert music of today and the most recorded music in the classical tradition. This course will focus on developments in European music during this critical period. An in-depth look at the music of Haydn, Mozart, and Beethoven along with the cultural and societal influences that shaped their lives will be the primary focus. Music of composers immediately preceding and following them (the Bach sons, Schubert, Chopin, and others) will also be surveyed. Instructor: Neenan.

Mu 139. History III: Music History from 1850 to the Present. *9 units (3-0-6); third term.* From the end of the 19th century to the present day, classical music has undergone the fastest and most radical changes in its history. The course explores these changes, tracing the development of various musical styles, compositional methods, and music technologies while examining acknowledged masterpieces from throughout the period. Instructor: Neenan.

Mu 140. The Great Orchestras: Their History, Repertoire, and Conductors. *9 units (3-0-6); second term.* This survey course will trace the symphony orchestra from its generally acknowledged beginnings with the Leipzig Gewandhaus Orchestra under Felix Mendelssohn to the present day. Special emphasis will be given to the great orchestras of the late nineteenth and twentieth centuries, their conductors, and the core orchestral repertoire. Making use of historic audio and video recordings from the twentieth century, along with more recent documentary recordings, students will be exposed to the cultural history of modern Europe and America through the medium of classical music. Not offered 2015–16.

NEUROBIOLOGY

Bi/CNS/NB 150. Introduction to Neuroscience. *10 units (4-0-6); first term.* For course description, see Biology.

Bi/CNS/NB 153. Brain Circuits. *9 units (3-0-6); second term.* For course description, see Biology.

Bi/NB/BE 155. Neuropharmacology. *6 units (3-0-3); second term.* For course description, see Biology.

Bi/NB 156. Molecular Basis of Behavior. *9 units (3-0-6); second term.* For course description, see Biology.

Bi/CNS/NB 157. Comparative Nervous Systems. *9 units (2-3-4); third term.* For course description, see Biology.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3); third term. Prerequisites: Bi/CNS/NB 150 or instructor's permission.* For course description, see Biology.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6); second term. Prerequisites: Bi/CNS/NB 150 or equivalent.* For course description, see Biology.

CNS/Bi/SS/Psy/NB 176. Cognition. *12 units (6-0-6); third term.* For course description, see Computation and Neural Systems.

Bi/CNS/NB 184. The Primate Visual System. *9 units (3-1-5); third term.* For course description, see Biology.

Bi/CNS/NB 185. Large Scale Brain Networks. *6 (2-0-4); third term.* For course description, see Biology.

CNS/Bi/EE/CS/NB 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4); second term.* For course description, see Computation and Neural Systems.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6); first term.* For course description, see Computation and Neural Systems.

Bi/CNS/NB 195. Mathematics in Biology. *9 units (3-0-6); second term.* For course description, see Biology.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units; summer.* For course description, see Bioengineering.

Bi/CNS/NB 216. Behavior of Mammals. *6 units (2-0-4); first term.* For course description, see Biology.

Bi/CNS/NB 217. Central Mechanisms in Perception. *6 units (2-0-4); first term.* For course description, see Biology.

Bi/CNS/NB 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. *9 units (3-2-4); third term.* For course description, see Biology.

CNS/Bi/NB 247. Cerebral Cortex. *6 units (2-0-4); second term.* For course description, see Computation and Neural Systems.

Bi/CNS/NB 250c. Topics in Systems Neuroscience. *9 units (3-0-6); third term.* For course description, see Biology.

CNS/Bi/NB 256. Decision Making. *6 units (2-0-4); third term.* For course description, see Computation and Neural Systems.

PERFORMANCE AND ACTIVITIES

Courses under this heading cover the instructional content of a range of extracurricular activities and work in the fine arts and elsewhere. These courses will appear on the student's transcript, and will be graded pass/fail only. The units count toward the total unit requirement for graduation, but they do not count toward the 108-unit requirement in humanities and social sciences.

PA 15abc. Student Publications. *3 units (1-0-2); first, second, third terms.* The elementary principles of newspaper writing and editing, with special attention to producing articles for the student publication. Instructor: Kipling.

PA 16 abc. Cooking Basics. *3 units (0-3-0); first, second, third terms.* The class will survey different cooking styles, techniques, and cuisines from around the world. Topics covered may include knives and tools; tastes and flavors; sauces and reductions; legumes, grains, and beans; meat; dessert. The emphasis will be on presentation and creativity. Instructor: Staff.

PA 30 abc. Guitar. *3 units (0-3-0); first, second, third terms.* Offered on three levels: beginning (no previous experience required), intermediate, and advanced. Instruction emphasizes a strong classical technique, including an exploration of various styles of guitar—classical, flamenco, folk, and popular. Instructor: Elgart.

PA 31 abc. Chamber Music. *3 units (0-3-0); first, second, third terms.* Study and performance of music for instrumental ensembles of two to eight members, and for piano four-hands. Literature ranges from the 16th to 21st centuries. Open to students who play string, woodwind, brass instruments, guitar, or piano. After auditioning, pianists will be placed in sections by the instructors. Section 1: Mixed ensembles. Instructor: D. Bing. Section 2: Piano four-hands. Instructor: Ward. Section 3: Guitar ensemble. Instructor: Elgart.

PA 32 abc. Symphony Orchestra. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for full symphony orchestra and chamber orchestra. The orchestra performs both the standard symphonic repertoire and contemporary music. Two and a half hours of rehearsal per week. Instructor: Gross.

PA 33 abc. Concert Band. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for the classical wind ensemble and concert band. Emphasis is placed on the traditional literature, but the study of contemporary music is an important part of the curriculum. Instructor: W. Bing.

PA 34 abc. Jazz Band. *3 units (0-3-0); first, second, third terms.* Study and performance of all styles of big-band jazz, from Duke Ellington to Maria Schneider. The study of jazz improvisation is also encouraged. Instructor: W. Bing.

PA 35 abc. W omen's Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of women's and SATB choral repertoire spanning a range of historical periods and musical styles. Includes collaborative performances with the Men's Glee Club and occasionally with orchestra. No previous experience required. Three hours a week. Instructor: Sulahian.

PA 36 abc. Men's Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of men's and SATB choral repertoire, spanning a range of historical periods and musical styles. Includes collaborative performances with the Women's Glee Club and occasionally with orchestra. No previous experience required. Three hours per week. Instructor: Sulahian.

PA 37 abc. Chamber Singers. *3 units (0-3-0); first, second, third terms.* Advanced study and performance of SATB choral music. Emphasis is placed on more difficult choral repertoire, both a capella and accompanied. Includes performances with the Glee Clubs as well as at other on-campus events. Audition required. Participation in Glee Clubs required. Instructor: Sulahian.

PA 40 abc. Theater Arts. *3 units (2-0-1); first, second, third terms.* Instruction in all phases of theatrical production, culminating in multiple performances for the public. A hands-on, practical approach includes workshops in stage combat, costume construction, scenic arts, occasional informal encounters with professional actors, designers, and directors. Understanding of dramatic structure, respect for production values, and problem solving are stressed. Material of academic value is drawn from 3,000 years of worldwide dramatic literature. Instructor: Brophy.

PA 61 abc. Silkscreen and Silk Painting. *3 units (0-3-0); first, second, third terms.* Instruction in silkscreening techniques, primarily for T-shirts. Progressive development of silk painting skills for fine art. Instructor: Barry.

PA 62 abc. Drawing and Painting. *3 units (0-3-0); first, second, third terms.* Instruction in techniques of painting in acrylics and watercolor and life drawing of models. Emphasis on student-chosen subject with a large reference library. Instructor: Barry.

PA 63 abc. Ceramics. *3 units (0-3-0); first, second, third terms.* Instruction in the techniques of creating ceramics, including the slab roller and potter's wheel, and glazing methods. Instructor: Freed.

PA 70 abc. Student-Taught Courses. *3 units (2-0-1); first, second, third terms.* A variety of subjects each term, taught by undergraduate students. Different subjects will fall under different section numbers. The courses offered each term will be decided based on student interest and a selection process by the Office of Student Affairs. More information at http://www.deans.caltech.edu/studenttaughtcourses.htm.

PHILOSOPHY

Hum/Pl 8. Right and Wrong. *9 units (3-0-6).* For course description, see Humanities.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6).* For course description, see Humanities.

Pl 90 ab. Senior Thesis. *9 units (1-0-8).* Required of students taking the philosophy option. To be taken in any two consecutive terms of the senior year. Students will research and write a thesis of 10,000–12,000 words on a philosophical topic to be determined in consultation with their thesis adviser. Limited to students taking the philosophy option. Instructor: Staff.

Pl 98. Reading in Philosophy. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in philosophy, in areas not covered by regular courses. Instructor: Staff.

Pl/Law 99. Causation and Responsibility. *9 units (3-0-6); first term.* This course will examine the interrelationships between the concepts of causation, moral responsibility, and legal liability. It will consider legal doctrines of causation and responsibility, as well as attempts within philosophy to articulate these concepts. Questions to be addressed include: Can you be morally or legally responsible for harms that you do not cause? Is it worse to cause some harm, than to unsuccessfully attempt it? Is it justified to punish those who cause harm more severely than those who attempt harm? When, if ever, can the ends justify the means? What constitutes negligence? Is it worse to cause some harm, than to allow it to happen (when you could have prevented it)? Not offered 2015–16.

Pl 100. Free Will. *9 units (3-0-6); first term.* This course examines the question of what it means to have free will, whether and why free will is desirable, and whether humans have free will. Topics may include historical discussions of free will from writers such as Aristotle, Boethius, and Hume; what it means for a scientific theory to be deterministic, and whether determinism is compatible with free will; the connection between free will and moral responsibility; the relationship between free will and the notion of the self; beliefs about free will; the psychology of decision making; and the insanity defense in law. Instructors: Hitchcock.

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6); offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or instructor's permission.*

Pl 103. Medieval Philosophy. *9 units (3-0-6); third term.* This course examines the philosophy of Western Europe from the decline of pagan culture to the Renaissance, roughly 400–1400 C.E. Material covered will vary, but will likely include a thorough introduction to Late Greek neo-Platonic philosophy as background to reading figures such as Augustine, Boethius, Avicenna, Abailard, Averroes, Maimonides, Anselm, Albert the Great, Aquinas, Olivi, Scotus, and Ockham. Not offered 2015–16.

HPS/Pl 120. Introduction to Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 122. Probability, Evidence, and Belief. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 123. Introduction to the Philosophy of Physics. *9 units (3-0-6); first term.* For course description, see History and Philosophy of Science.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 125. Philosophical Issues in Quantum Physics. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

HPS/Pl 128. Philosophy of Mathematics. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 129. Introduction to Philosophy of Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 135. Moral Philosophy and the Brain. *9 units (3-0-6); second term.* For course description, see History and Philosophy of Science.

HPS/Pl 136. Happiness and the Good Life. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

HPS/Pl 138. Human Nature and Society. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Pl 150. 17th-Century Philosophy: Bacon to Leibniz. *9 units (3-0-6); second terms.* The course will examine the work of one or more philosophers active during the so-called Century of Genius. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include the limits of human knowledge, the existence and nature of mind, matter, and God, and the relationship between science and philosophy. Philosophers discussed are selected from Bacon, Mersenne, Descartes, Gassendi, Hobbes, Digby, Spinoza, Malebranche, Arnauld, More, Cudworth, Locke, Newton, and Leibniz. Not offered 2015–16.

Pl 151. 18th-Century Philosophy: Locke to Kant. *9 units (3-0-6); first term.* The course will examine the work of one or more philosophers active during the so-called Age of Enlightenment. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include ideas and perception, belief and knowledge, passion and reason, matter and mind, causation and free will, and the relationship between science and philosophy. Philosophers discussed are selected from Locke, Huygens, Leibniz, Newton, Wolff, Berkeley, Rousseau, Hume, Reid, and Kant. Not offered 2015–16.

HPS/Pl 165. Selected Topics in Philosophy of Science. *9 units (3-0-6);* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6); second term.* For course description, see History and Philosophy of Science.

HPS/H/Pl 176. History of Alchemy. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

Pl/HPS 183. Bioethics. *9 units (3-0-6); offered by announcement.* A survey of issues in bioethics. Topics may include: abortion and reproductive rights; euthanasia; cloning; genetic modification of organisms (including humans); moral status of chimeras; stem-cell research; organ transplantation, distribution and sale; cure vs. enhancement; use of human subjects in research; the concept of informed consent; research on non-human animals. Instructors: Cowie, Manning.

Pl 185. Moral Philosophy. *9 units (3-0-6); third term.* A survey of topics in moral philosophy. The emphasis will be on metaethical issues, although some normative questions may be addressed. Metaethical topics that may be covered include the fact/value distinction; the nature of right and wrong (consequentialism, deontological theories, rights-based ethical theories, virtue ethics); the status of moral judgments (cognitivism vs. noncognitivism, realism vs. irrealism); morality and psychology; moral relativism; moral skepticism; morality and self-interest; the nature of justice. The implications of these theories for various practical moral problems may also be considered. Not offered 2015–16.

Pl 186. Political Philosophy. *9 units (3-0-6); offered by announcement.* This course will address one or more issues in contemporary political theory and/or the history of political thought. Topics may include the nature of democracy; liberalism; distributive justice; human rights; the moral and legal regulation of warfare; the status of positive law; social choice theory; the relations between the market and the state. The work of figures such as Plato, Aristotle, Locke, Hobbes, Mill, Machiavelli, and Rawls will be discussed. Not offered 2015–16.

HPS/Pl 188. The Evolution of Cognition. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

PHYSICAL EDUCATION

PE 1. Student Designed Fitness. *3 units; first, second, third terms; May only be used for 3 units of the 9-unit physical education requirement.* This course provides students with knowledge and practical opportunities to develop and implement an individualized program to successfully accomplish their physical fitness goals. Detailed proposals are developed during week two of the term, and journals are maintained throughout the term to monitor progress. Instructors: Staff

PE 2. Healthier Living. *3 units; second term. May only be used for 3 units of the 9-unit physical education requirement.* This course is designed to educate students and increase awareness of the dimensions of health and wellness. The course will be implemented through personal assessment, active participation, guest lectures, and engaging dialogue. In addition, the course will emphasize positive personal healthful decisions and encourage students to adopt behaviors to minimize health risks, enhance overall wellness, and foster healthy active lifestyles across the lifespan. Instructor: Staff

PE 3. Hiking. *3 units; first, second, third terms.* This course is designed to provide students an opportunity to explore the outdoors of Pasadena and the San Gabriel Mountains while participating in physical fitness activities. Learn about proper hiking gear, basics for safety, trip plans, and how to research trails in the local area. The class will meet on campus and then travel to one of the local trails for an afternoon hike. Students will be asked to use maps, compass, and GPS devices on various hikes to teach them proper use of all forms of location guidance. Along the trail, students will be asked to identify local flora and vegetation, learn trail etiquette, discuss survival scenarios in the event of emergency, and practice basic trail first aid. Topics such as trail nutrition and hydration will be presented, and students will create a search and rescue plans in the event of an overnight emergency. *This class will only be offered on Friday afternoon in the fall and spring, meeting once per week for a three hour block to accomodate travel off campus.* Instructor: Staff.

PE 4. Introduction to Power Walking. *3 units; third term.* Introduction to walking for fitness. Emphasis on cardiovascular benefits for a healthy lifestyle. The program is progressive and suitable for walkers of all levels. Instructor: Staff.

PE 5. Beginning Running - Half Marathon Training. *3 units; third term.* This course helps anyone learn to conquer the distance of a half marathon, regardless of your previous running experience. Beginners welcome! Learn to complete a distance event using the Jeff Galloway method of training., which employs run/walk cycles to provide runners with rest and recovery while tackling the long mileage of a half marathon. This course will give students a training schedule, determine the individually appropriate run walk ratio, and help students find an appropriate pace that fits their running ability. Class sessions include a short lecture and run, with students designing a long run course for themselves and running longer mileage on a third day outside of class meetings. Short topics such as hydration, nutrition, race strategy, proper clothing, and shoe choices will be given at the beginning of each session. Speed work options are provided for runners who want to increase their pace. Students are encouraged but not required to pick a race to participate in toward the end of the term. Instructor: Staff.

PE 6. Core Training, Beginning/Intermediate. *3 units; first, second, third terms.* Learn to develop functional fitness using core stability training techniques that focus on working deep muscles of the entire torso at once. The course is taught using exercises that develop core strength, including exercises on a stability ball, medicine ball, wobble boards as well as with Pilates exercise programs. Instructor: Staff.

PE 7. Speed and Agility Training, Beginning/Intermediate. *3 units; second term.* Instruction to increase foot speed and agility with targeted exercises designed to help the student increase these areas for use in competitive situations. Instruction will focus on increasing foot speed, leg turnover, sprint endurance, and competitive balance. Proper technique and specific exercises as well as development of an individual or sport-specific training workout will be taught. Instructor: Staff.

PE 8. Fitness Training, Beginning. *3 units; first, second, third terms.* An introductory course for students who are new to physical fitness. Students will be introduced to different areas of fitness such as weight training, core training, walking, aerobics, yoga, swimming, and cycling. Students will be able to design an exercise program for lifelong fitness. Instructor: Staff.

PE 9. Soccer. *3 units; third term.* Fundamental instruction on shooting, passing, trapping, dribbling, penalty kicks, offensive plays, defensive strategies, and goal keeping. Course includes competitive play using small field and full field scrimmages. Instructor: Staff.

PE 10. Aerobic Dance. *3 units; first, second, third terms.* Each class includes a thorough warm-up, a cardiovascular workout phase that includes a variety of conditioning exercises designed to tone and strengthen various muscle groups, and a relaxation cool-down and stretch, all done to music. Instructor: Staff.

PE 14. Basketball Skills, Beginning and Beginning/Intermediate. *3 units; third term.* Features fundamental instruction on shooting, dribbling, passing, defensive positioning, and running an offense. Course includes competitive play and free-throw shooting. Instructors: Staff.

PE 20. Fencing, Beginning and Intermediate/Advanced. *3 units; first term.* Beginning fencing includes basic techniques of attack, defense, and counter-offense. Lecture topics include fencing history, strategy, scouting and analysis of opponents, and gamesmanship. Intermediate/ Advanced covers foil theory and techniques, group drillwork, and video analysis. Instructor: Staff.

PE 24. Yoga, Beginning. *3 units; first, second, third terms.* Hatha Yoga is a system of physical postures designed to stretch and strengthen the body, calm the nervous system, and center the mind. It is a noncompetitive activity designed to reduce stress for improved health of body and mind while increasing flexibility, strength, and stamina, and reducing chance of athletic injury. Instructor: Staff.

PE 27. Ultimate Frisbee. *3 units; third term.* Instruction will center on developing students' knowledge of techniques, rules, strategy, etiquette, and safety regulations of the game. Students will develop the ability to perform all skills necessary to play the game confidently on a recreational basis. Instructor: Staff.

PE 28. Flying Saucers. *3 units; first, second terms.* This course is designed to provide students an opportunity to learn proper techniques, form, rules, and game play for various Frisbee activities including Frisbee golf, Frisbee tag, and Ultimate Frisbee while promoting healthy lifestyle behaviors. Students will also improve hand-eye coordination, agility, and foot speed. Instructors: Staff.

PE 30. Golf, Beginning, Intermediate, and Advanced. *3 units; second, third terms.* Beginning course covers fundamentals of the game, including rules, terminology, etiquette, basic grip, set-up, swing, and club selection for each shot. The following shots will be covered: full swing (irons and woods), chip, pitch, sand, and putting. Intermediate course will focus on swing development of specialty shots and on course play management. Advanced instruction covers course management and mental aspects of performance. Instructor: Staff.

PE 31. Indoor/Outdoor Cycling. *3 units; first term.* During this introductory course surveying a variety of cycling disciplines including mountain biking, road biking, cyclocross, velodrome, and indoor cycling, students will learn proper cycling techniques, bike handling, set-up, safety, and maintenance. Students will also learn and apply principles of lifetime physical fitness utilizing major components of cardio-respiratory endurance, muscular strength and endurance, and flexibility. It is recommended students have a bicycle however a limited number of bikes will be provided as needed. Students will be required to have and wear a helmet for all class cycling activities. Instructors: Staff.

PE 33. Beginning Triathlon Training. *3 units; first term.* This course is designed to help beginners learn to train for a sprint distance triathlon. All three disciplines will be taught, with specific technique instruction in each area. Students will learn how to develop a training schedule, choosing the correct event for their skill, nutrition, safety, and race preparation. The course will include techniques to increase transition efficiency, trouble shoot issues on the route and strategies to record a personal best in future races. Safe training to reduce injury and assure a healthy race is the foundation of this course. Instructor: Staff.

PE 35. Diving, Beginning/Intermediate. *3 units; first term.* Students will learn fundamentals of springboard diving to include basic approach, and five standard dives. Intermediate course includes instruction in the back somersault, forward somersault, forward somersault full twist, and reverse somersault. Instructor: Staff.

PE 36. Swimming, Beginning/Intermediate and Advanced. *3 units; first, second, third terms.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Advanced course focuses on proper technique of the four competitive strokes using video and drills along with instruction on training methods and proper workout patterns. Instructor: Staff.

PE 37. Beginning Kayaking. *3 units; first term.* This course will provide instruction in basic kayaking skills including kayaking outfitting, stroke technique, self-rescue and kayak maneuvering. The goal is for students to learn to navigate turbulent ocean waters or through whitewater rapids on rivers. No kayaking experience is required. Instruction will focus on whitewater application to ocean kayaking. Students will learn basic paddle techniques and craft control, and a self rescue technique progression culminating in the C-to-C kayak roll. Trips to local bays and rivers will be included and are optional. Class meetings will be held in the Caltech pool. Course Requirement - Students must be a proficient swimmer or be able to successfully complete an in water swim test. Instructors: Staff.

PE 38. Water Polo. *3 units; second term.* Basic recreational water polo with instruction of individual skills and team strategies. A background in swimming is encouraged. Instructor: Staff.

PE 40. Beginning Self Defense. *3 units.* Students will learn basics of keeping themselves safe when an unknown person threatens their safety. The course is focused on staying safe while rendering an assailant temporarily unable to give chase to allow the student to get help. Techniques taught will assist students in learning vulnerable targets to disable an attacker, using their own body to maximize damage to allow escape, and finding methods to generate force. Using an assailant's attack against him to maintain balance and administer the greatest degree of force necessary to disable a threat is the foundation of the course.

PE 44. Karate (Shotokan), Beginning and Intermediate/ Advanced. *3 units; first and third terms.* Fundamental self-defense techniques including form practice and realistic sparring. Emphasis on improving muscle tone, stamina, balance, and coordination, with the additional requirement of memorizing one or more simple kata (forms). Instructor: Staff.

PE 46. Karate (Tang Soo Do), Beginning and Intermediate/Advanced. *3 units.* Korean martial art focusing on self-defense and enhancement of physical and mental health. Practical and traditional techniques such as kicks, blocks, hyungs (forms) are taught. Intermediate/Advanced level incorporates technique combinations, sparring skills, jumping and spinning kicks, and history and philosophy.

PE 48. T'ai-Chi Ch'uan, Beginning and Intermediate/ Advanced. *3 units; second term.* Chinese movement art emphasizing relaxation and calm awareness through slow, flowing, meditative movement using only minimum strength needed to accomplish the action. Instructor: Staff.

PE 50. Badminton, Beginning/Intermediate. *3 units; third term.* Basic skills will be taught, including grips, services, overhead and underhand strokes, and footwork. Rules, terminology, and etiquette are covered. Intermediate skills such as drives, serve returns, forehand and backhand smash returns, attacking clears, and sliced drop shots are taught. Singles and doubles play along with drill work throughout the term. Instructor: Staff.

PE 54. Racquetball, Beginning and Intermediate/Advanced. *3 units; first, second, third term.* Fundamentals of the game will be emphasized, including rules, scoring, strategy, and winning shots. All types of serves will be covered, as well as a variety of shots to include kill, pinch-off, passing, ceiling, and off-the-backwall. Singles and doubles games will be played. Intermediate/Advanced course will review all fundamentals with a refinement of winning shots, serves, and daily games. Instructor: Staff.

PE 56. Squash, Beginning, Intermediate, Advanced. *3 units; second term.* Learn by playing as basic rules and strokes are taught. Fundamentals to include proper grip, stroke, stance, and positioning, along with serve and return of serve. Intermediate and Advanced course will concentrate on skill development with inclusion of forehand and backhand drives, lobs, volleys, and drops, with emphasis on court movement, shot selection, and tactics. Instructor: Staff.

PE 60. Tennis, Beginning, Intermediate, and Advanced. *3 units; first, second, third terms.* Stroke fundamentals, singles and doubles play, plus rules, terminology, and etiquette are covered in all classes. Beginning course emphasizes groundstrokes, volleys, serve, and grips. Beginning/ Intermediate course is for those players between levels and will concentrate on strategy, drills, and match play. Intermediate level focuses on improving technique, footwork, and court positioning, with instruction on approach shots, volleys, overheads, and lobs. Advanced course fine tunes each individual's skills while targeting weaknesses. Instructor: Staff.

PE 70. Weight Training, Beginning/Intermediate. *3 units; first, second, third terms.* Active participation in a strength and conditioning program designed for individual skill level and desired effect. Course will enlighten students on various methods, terminology, and techniques in isokinetic strength and cardiovascular fitness training. Instructor: Staff.

PE 71. Advanced Techniques of Human Performance. *3 units; first, third terms.* Prerequisites: PE 70, instructor approval . This course is intended for those experienced with high level physical training. This course helps individuals improve sport and physical fitness skills by addressing components including muscular strength, foot speed, agility, cardiovascular conditioning and flexibility. Instructor: Staff.

PE 77. Volleyball, Beginning, Intermediate, and Advanced. *3 units; third term.* Fundamental instruction on drills, strategies, and rules, with game-playing opportunities. Basics of serve, pass, set, spike, defense, and court position will be taught. Intermediate level focuses on skill development to a more competitive standard and features multiple offenses and understanding officiating. Advanced courses emphasizes specialization of all skills, court position, and multiple offenses and defenses. Instructor: Staff.

PE 80 abc. Health Advocates. *3 units (1-1-1); first, second, third terms. Does not satisfy the Institute physical education requirement.* A course designed to involve students with health care and education, develop familiarity with common college health problems, and provide peer health services on and off campus. First term: CPR and first aid certification and basic anatomy and physiology. Second and third terms: lectures and discussions on current student and community health problems, symptoms, and treatment. Each student will be expected to devote one hour per week to a supervised clinical internship at the Health Center. Instructor: Stapf.

PE 81. Bouldering. *3 units; first, second term. Taught at the Caltech bouldering cave, Brown Gym.* During this introductory course to bouldering, students will learn terminology, how to properly fit into a harness, set-up and use a tubular belay device, and belay commands. This course will emphasize muscle strength and endurance, balance, and flexibility, as well as be challenging for mind and body. Instructors: Staff.

PE 82. Rock Climbing, Beginning/Intermediate. *3 units; first, second, third terms. Taught at the Caltech Climbing Wall, Brown Gym.* Basic skills will be covered to utilize each student's strength and endurance while learning to climb safely. Use of climbing rope and other equipment for belaying, rappelling, and emergency ascent will be taught. Instructor: Staff.

PE 84. Table Tennis, Beginning/Intermediate. *3 units; second term.* Introductory course to provide general knowledge of equipment, rules, and basic strokes, including topspin drive, backspin chop, and simple block in both forehand and backhand. Multiball exercise utilizing robot machines and video. Intermediate class covers regulations for international competition and fundamentals of winning table tennis, including footwork drills, smash, serve, and attack. Instructor: Staff.

Intercollegiate Teams

PE 83 ab. Intercollegiate Basketball Team (Women). *3 units; first, second terms.* Coach: Marbut.

PE 85 ab. Intercollegiate Track and Field Team (Men and Women). *3 units; second, third terms.* Coach: Raphelson.

PE 87 ab. Intercollegiate Swimming Team (Men and Women).
3 units; first, second terms. Coach: Leavitt.

PE 89 ab. Intercollegiate Fencing Team (Men and Women). *3 units; first, second terms.* Coach: Corbit.

PE 90 abc. Intercollegiate Water Polo Team (Men and Women). *3 units; first term Men; second, third term Women.* Coach: Staff.

PE 91 ab. Intercollegiate Basketball Team (Men). *3 units; first, second terms.* Coach: Eslinger.

PE 92. Intercollegiate Soccer Team (Men). *3 units; first term.* Coach: Murray

PE 93 ab. Intercollegiate Baseball Team (Men). *3 units; second, third terms.* Coach: Mark.

PE 95 ab. Intercollegiate Tennis Team (Men). *3 units; second, third terms.* Coach: Gamble.

PE 96 ab. Intercollegiate Tennis Team (Women). *3 units; second, third terms.* Coach: Gamble.

PE 97. Intercollegiate Cross-Country Team (Men and Women). *3 units; first term.* Coach: Raphelson.

PE 99. Intercollegiate Volleyball Team (Women). *3 units; first term.* Coach: Gardner.

PHYSICS

Ph 1 abc. Classical Mechanics and Electromagnetism. *9 units (4-0-5); first, second, third terms.* The first year of a two-year course in introductory classical and modern physics. Topics: Newtonian mechanics in Ph 1 a; electricity and magnetism, and special relativity, in Ph 1 b, c. Emphasis on physical insight and problem solving. Ph 1 b, c is divided into two tracks: the Practical Track emphasizing practical electricity, and the Analytic Track, which teaches and uses methods of multivariable calculus. Students enrolled in the Practical Track are encouraged to take Ph 8 bc concurrently. Students will be given information helping them to choose a track at the end of fall term. Instructors: Patterson, Hsieh, Martin, Alicea.

Ph 2 abc. Waves, Quantum Mechanics, and Statistical Physics. *9 units (3-0-6) ; first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc.* An introduction to several areas of physics including applications in modern science and engineering. Topics include discrete and continuous oscillatory systems, wave mechanics, applications in telecommunications and other areas (first term); foundational quantum concepts, the quantum harmonic oscillator, the Hydrogen atom, applications in optical and semiconductor systems (second term); ensembles and statistical systems, thermodynamic laws, applications in energy technology and other areas (third term). Although best taken in sequence, the three terms can be taken independently. Instructor: Martin, Politzer, Cheung, Filippone.

Ph 3. Physics Laboratory. *6 units (0-3-3); first, second, third terms. Prerequisite: Ph 1 a or instructor's permission.* An introduction to experimental techniques and instruments used in the physical sciences, covering topics in classical mechanics, basic electronic circuits, and optics. Special emphasis is given to data analysis techniques based on modern statistical methods. The weekly structure of the course includes one three-hour laboratory session, a conference with the instructor, a set of pre-lab problems, and analysis of experimental results. Graded pass/fail unless a letter grade is requested. Only one term may be taken for credit. Instructors: Black, Libbrecht.

FS/Ph 4. Freshman Seminar: Astrophysics and Cosmology with Open Data. *6 units (3-0-3); first term.* For course description, see Freshman Seminar.

Ph 5. Analog Electonics for Physicists. *9 units (0-5-4); first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (Ph 8 may be subsituted for Ph 3).* A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Libbrecht.

Ph 6. Physics Laboratory. *9 units; second term. Prerequisites: Ph 1 abc, Ph 2 b or Ph 12 b (or taken concurrently), and Ph 3 or equivalent.* Experiments in electromagnetic phenomena such as electromagnetic induction, properties of magnetic materials, and high-frequency circuits. Mobility of ions in gases; precise measurement of the value of e/m of the electron. Instructors: Rice, Politzer.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisites: Ph 6.* Experiments in atomic and nuclear physics, including studies of the Balmer series of hydrogen and deuterium, the decay of radioactive nuclei, absorption of X rays and gamma rays, ratios of abundances of isotopes, and the Stern-Gerlach experiment. Instructors: Rice, Politzer.

Ph 8 bc. Experiments in Electromagnetism. *3 units (0-3-0); second, third terms. Prerequisite: Ph 1 a.* A two-term sequence of experiments that parallel the material of Ph 1 bc. It includes measuring the force between wires with a homemade analytical balance, measuring properties of a 1,000-volt spark, and building and studying a radio-wave transmitter and receiver. The take-home experiments are constructed from a kit of tools and electronic parts. Measurements are compared to theoretical expectations. Instructor: Spiropulu.

FS/Ph 9. Freshman Seminar: The Science of Music. *6 units (2-0-4).* For course description, see Freshman Seminar.

Ph 10. Frontiers in Physics. *3 units (2-0-1); first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the physics department or a visitor, to discuss his or her research at an introductory level; the other class meetings will be used to explore background material related to seminar topics and to answerh questions that arise. The course will also help students find faculty sponsors for individual research projects. Graded pass/fail. Instructor: Soifer.

FS/Ph 11 abc. Research Tutorial. *6 units (2-0-4).* For course description, see Freshman Seminar.

Ph 12 abc. Waves, Quantum Physics, and Statistical Mechanics. *9 units (4-0-5); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, or equivalents.* A one-year course primarily for students intending further work in the physics option. Topics include classical waves; wave mechanics, interpretation of the quantum wave-function, one-dimensional bound states, scattering, and tunneling; thermodynamics, introductory kinetic theory, and quantum statistics. Instructors: Chen, Filippone, Preskill.

FS/Ph 15. Freshman Seminar: Dance of the Photons. *6 units (2-0-4); second term.* For course description, see Freshman Seminar.

Ph 20. Computational Physics Laboratory I. *6 units (0-6-0); first, second, third terms. Prerequisites: CS 1 or equivalent.* Introduction to the tools of scientific computing. Use of numerical algorithms and symbolic manipulation packages for solution of physical problems. Python for scientific programming, Mathematica for symbolic manipulation, Unix tools for software development. Instructors: Mach, Weinstein.

Ph 21. Computational Physics Laboratory II. *6 units (0-6-0); second, third terms. Prerequisites: Ph 20 or equivalent experience with programming.* Computational tools for data analysis. Use of python for accessing scientific data from the web. Bayesian techniques. Fourier techniques. Image manipulation with python. Instructors: Mach, Weinstein.

Ph 22. Computational Physics Laboratory III. *6 units (0-6-0); third term. Prerequisites: Ph 20 or equivalent experience with programming and numerical techniques.* Computational tools and numerical techniques. Applications to problems in classical mechanics. Numerical solution of 3-body and N-body systems. Monte Carlo integration. Instructors: Mach, Prince.

Ph 50 abc. Caltech Physics League. *4 units (1-0-3); first, second terms. Prerequisite: Ph 1 abc.* This course serves as a physics club, meeting weekly to discuss and analyze real-world problems in the physical sciences. A broad range of topics will be considered, such as energy production, space and atmospheric phenomena, astrophysics, nano-science, and others. Students will use basic physics knowledge to produce simplified (and perhaps speculative) models of complex natural phenomena. In addition to regular assignments, students will also compete in solving challenge problems each quarter, with prizes given in recognition of the best solutions. Instructor: Refael.

Ph 70. Oral and Written Communication. *6 units (2-0-4); first, third terms.* Provides practice and guidance in oral and written communication of material related to contemporary physics research. Students will choose a topic of interest, make presentations of this material in a variety of formats, and, through a guided process, draft and revise a technical or review article on the topic. The course is intended for senior physics majors. *Fulfills the Institute scientific writing requirement.* Instructor: Hitlin.

Ph 77 abc. Advanced Physics Laboratory. *9 units (0-5-4); first, second, third terms. Prerequisite: Ph 7 or instructor's permission.* A three-term laboratory course to familiarize students with equipment and procedures used in the research laboratory. Experiments illustrate fundamental physical phenomena in atomic, optical, condensed-matter, nuclear, and particle physics, including NMR, laser-based atomic spectroscopy, gamma and X-ray spectroscopy, muon decay, weak localization, superconductivity, positron annihilation, and others. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, the student's thesis adviser. Laboratory work is required for this course. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Ph 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Note: Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the chair of the Physics Undergraduate Committee, or any other member of this committee.
A grade will not be assigned in Ph 78 or Ph 79 until the end of the third term. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ph 101. Order-of-Magnitude Physics. *9 units (3-0-6); third term.* Emphasis will be on using basic physics to understand complicated systems. Examples will be selected from properties of materials, geophysics, weather, planetary science, astrophysics, cosmology, biomechanics, etc. Not offered 2015–16.

Ph 103. Atomic and Molecular Spectroscopy. *9 units (3-0-6); second term. Prerequisites: instructor's permission.* This course will review the basic spectroscopy of atoms and molecules, with applications to astrophysics, the terrestrial atmosphere, and the laboratory. Species to be discussed include hydrogen and simple multielectron atoms such as carbon, diatomic and polyatomic molecules, and some solids. Mechanisms and effects determining linewidths and lineshapes will be discussed for laboratory, atmospheric, and astrophysical conditions. Not offered 2015–16.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6).* For course description, see Astrophysics.

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (Ph 8 may be substituted for Ph 3).* A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Libbrecht

Ph 106 abc. Topics in Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 ab or Ph 12 abc, Ma 2.* An intermediate course in the application of basic principles of classical physics to a wide variety of subjects. Roughly half of the year will be devoted to mechanics, and half to electromagnetism. Topics include Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, boundary-value problems, multipole expansions, and various applications of electromagnetic theory. Instructors: Golwala, Chen.

APh/Ph 115. Physics of Momentum Transport in Hydrodynamic Systems. *12 units (3-0-9).* For course description, see Applied Physics.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. *12 units (3-0-9).* For course description, see Applied Physics.

Ph/APh/EE/BE 118 ab. Physics of Measurement. *9 units (3-0-6); first and second terms. Prerequisites: Ph127, APh 105, or equivalent, or permission from instructor.* This course focuses on exploring the fundamental underpinnings of experimental measurements from the perspectives of responsivity, noise, backaction, and information. Its overarching goal is to enable students to critically evaluate real measurement systems, and to determine the ultimate fundamental and practical limits to information that can be extracted from them. Topics will include physical signal transduction and responsivity, fundamental noise processes, modulation, frequency conversion, synchronous detection, signal-sampling techniques, digitization, signal transforms, spectral analyses, and correlations. The first term will cover the essential fundamental underpinnings, while topics in second term will include examples from optical methods, high-frequency and fast temporal measurements, biological interfaces, signal transduction, biosensing, and measurements at the quantum limit. Instructor: Roukes.

Ph/APh/EE/BE 118 c. Physics of Measurement. *9 units (3-0-6); third terms. Prerequisites: Ph127, APh 105, or equivalent, or permission from instructor.* Ph118c will focus on the physical principles and applications of several important measurement techniques to modern condensed matter physics research. The course will begin with an introduction of the concept of self-energy and Green function techniques in the descriptions of many-body interactions. Several representative experimental techniques for investigating important physical properties of many-body systems will be discussed, followed by explicit examples for their applications to condensed matter physics research. The measurement techniques will include scanning probe microscopy, angle-resolved photoemission spectroscopy, optical measurements, and thermodynamic and electrical transport measurements. Instructor: Yeh.

Ph 125 abc. Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 ab, Ph 12 abc or Ph 2 ab, or equivalents.* A one-year course in quantum mechanics and its applications, for students who have completed Ph 12 or Ph 2. Wave mechanics in 3-D, scattering theory, Hilbert spaces, matrix mechanics, angular momentum, symmetries, spin-$^1/_2$ systems, approximation methods, identical particles, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructors: Wise, Cheung.

Ph 127 abc. Statistical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 12 c or equivalent, and a basic understanding of quantum and classical mechanics.* A course in the fundamental ideas and applications of classical and quantum statistical mechanics. Topics to be covered include the statistical basis of thermodynamics; ideal classical and quantum gases (Bose and Fermi); lattice vibrations and phonons; weak interaction expansions; phase transitions; and fluctuations and dynamics. Instructor: Alicea, Motrunich, Refael.

Ph 129 abc. Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc and ACM 95/100 ab or Ma 108 abc, or equivalents.* Mathematical methods and their application in physics. First term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. Second term covers probability and statistics in physics. Third term focuses on group theoretic methods in physics. The three terms can be taken independently. Instructors: Porter, Chen.

Ph 135 abc. Applications of Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 125 abc or equivalent.* Applications of quantum mechanics to topics in contemporary physics. First term: introduction to condensed matter which covers electronic properties of solids, including band structures, transport, and optical properties. Ph 135a is continued by Ph 223 ab in second and third terms. Second term: introduction to particle physics which includes Standard Model, Feynman diagrams, matrix elements, electroweak theory, QCD, gauge theories, the Higgs mechanism, neutrino mixing, astro-particle physics/cosmology, accelerators, experimental techniques, important historical and recent results, physics beyond the Standard Model, and major open questions in the field. Third term: an overview of modern Quantum Optics with particular emphasis on quantum measurement science, the quantum-classical interface, quantum networks, and quantum many-body physics with atoms and photons. The course will concentrate on the essential roles of manifestly quantum (i.e., nonclassical) and entangled states of light and matter. The course covers theoretical tools for analyses of coherent light-matter interactions including the quantum master equation, and will combine examples on both theory and experiment from the current research literature. This is a one-term class aimed at advanced undergraduates as well as beginning graduate students. Terms may be taken independently. Instructors: Motrunich, Patterson, Kimble.

Ph 136 abc. Applications of Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc or equivalent.* Applications of classical physics to topics of interest in contemporary "macroscopic" physics. Continuum physics and classical field theory; elasticity and hydrodynamics; plasma physics; magnetohydrodynamics; thermodynamics and statistical mechanics; gravitation theory, including general relativity and cosmology; modern optics. Content will vary from year to year, depending on the instructor. An attempt will be made to organize the material so that the terms may be taken independently. Ph 136a will focus on thermodynamics, statistical mechanics, random processes, and optics. Ph136b will focus on fluid dynamics, MHD, turbulence, and plasma physics. Ph 136c will cover an introduction to general relativity. Instructors: Ott, Scheel.

Ph 171. Reading and Independent Study. *Units in accordance with work accomplished.* Occasionally, advanced work involving reading, special problems, or independent study is carried out under the supervision of an instructor. Approval of the instructor and of the student's departmental adviser must be obtained before registering. The instructor will complete a student evaluation at the end of the term. Graded pass/fail.

Ph 172. Research in Experimental Physics. *Units in accordance with work accomplished.* Students registering for 6 or more units of Ph 172 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics. *Units in accordance with work accomplished.* Students registered for 6 or more units of Ph 173 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph 199. Frontiers of Fundamental Physics. *9 units (3-0-6); third term. Prerequisites: Ph 125 abc, Ph 106 abc, or equivalent.* This course will explore the frontiers of research in particle physics and cosmology, focusing on the physics at the Large Hadron Collider. Topics include the Standard Model of particle physics in light of the discovery of the Higgs boson, work towards the characterization and measurements of the new particle's quantum properties, its implications on physics beyond the standard model, and its connection with the standard model of cosmology focusing on the dark matter challenge. The course is geared toward seniors and first-year graduate students who are not in particle physics, although students in particle physics are welcome to attend. Not offered 2015–2016.

Ph 205 abc. Relativistic Quantum Field Theory. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 125.* Topics: the Dirac equation, second quantization, quantum electrodynamics, scattering theory, Feynman diagrams, non-Abelian gauge theories, Higgs symmetry-breaking, the Weinberg-Salam model, and renormalization. Instructors: Gukov, Wise.

Ph 217. Introduction to the Standard Model. *9 units (3-0-6); first term. Prerequisites: Ph 205 abc and Ph 236 abc, or equivalent.* An introduction to elementary particle physics and cosmology. Students should have at least some background in quantum field theory and general relativity. The standard model of weak and strong interactions is developed, along with predictions for Higgs physics and flavor physics. Some conjectures for physics beyond the standard model are introduced: for example, low-energy supersymmetry and warped extra dimensions. Instructors: Cheung.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 129 abc or equivalent.* The theory of quantum information and quantum computation. Overview of classical information theory, compression of quantum information, transmission of quantum information through noisy channels, quantum error-correcting codes, quantum cryptography and teleportation. Overview of classical complexity theory, quantum complexity, efficient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructors: Kitaev, Preskill.

Ph/APh 223 ab. Advanced Condensed-Matter Physics. *9 units (3-0-6); second, third terms. Prerequisites: Ph 125 or equivalent, or instructor's permission.* Advanced topics in condensed-matter physics, with emphasis on the effects of interactions, symmetry, and topology in many-body systems. Ph/Aph 223a covers second quantization, Hartree-Fock theory of the electron gas, Mott insulators and quantum magnetism, bosonization, quantum Hall effects, and symmetry protected topological phases such as topological insulators. Ph/APh 223b will continue with BCS theory of superconductivity, Ginzburg-Landau theory, elements of unconventional and topological superconductors, theory of superfluidity, Bose-Hubbard model and bosonic Mott insulators, and some aspects of quantum systems with randomness. Instructors: Alicea, Motrunich.

Ph 229 abc. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first term. Prerequisite: Ph 129 abc or equivalent.* Advanced topics in geometry and topology that are widely used in modern theoretical physics.

Emphasis will be on understanding and applications more than on rigor and proofs. First term will cover basic concepts in topology and manifold theory. Second term will include Riemannian geometry, fiber bundles, characteristic classes, and index theorems. Third term will include anomalies in gauge-field theories and the theory of Riemann surfaces, with emphasis on applications to string theory. Instructor: Kapustin.

Ph 230 abc. Elementary Particle Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ph 205 abc or equivalent.* Advanced methods in quantum field theory. First term: introduction to supersymmetry, including the minimal supersymmetric extension of the standard model, supersymmetric grand unified theories, extended supersymmetry, supergravity, and supersymmetric theories in higher dimensions. Second and third terms: nonperturbative phenomena in non-Abelian gauge field theories, including quark confinement, chiral symmetry breaking, anomalies, instantons, the 1/N expansion, lattice gauge theories, and topological solitons. Instructor: Kapustin

Ph 236 abc. Relativity. *9 units (3-0-6); first, second terms. Prerequisite: a mastery of special relativity at the level of Goldstein's* Classical Mechanics*, or of Jackson's* Classical Electrodynamics. A systematic exposition of Einstein's general theory of relativity and its applications to gravitational waves, black holes, relativistic stars, causal structure of space-time, cosmology and brane worlds. Not offered 2015–2016.

Ph 237. Gravitational Waves. *9 units (3-0-6); third term. Prerequisite: Ph 236 a.* The theory and astrophysical phenomenology of gravitational-wave sources (black holes, neutron stars, compact binaries, early-universe phenomena, etc.). Gravitational-wave detectors (LIGO, LISA, and others), and data analysis. Not offered 2015–16.

Ph 242 ab. Physics Seminar. *3 units (2-0-1); first, second terms.* Topics in physics emphasizing current research at Caltech. One two-hour meeting per week. Speakers will be chosen from both faculty and students. Registration restricted to first-year graduate students in physics; exceptions only with permission of instructor. Graded pass/fail. Instructor: Stone.

Ph 250 abc. Introduction to String Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 or equivalent.* The first two terms will focus largely on the bosonic string. Topics covered will include conformal invariance and construction of string scattering amplitudes, the origins of gauge interactions and gravity from string theory, T-duality, and D-branes. The third term will cover perturbative aspects of superstrings, supergravity, various BPS branes, and string dualities. Not offered 2015–16.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 or Ph 173 when the student has progressed to the point where research leads directly toward the thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

POLITICAL SCIENCE

PS 12. Introduction to Political Science. *9 units (3-0-6); first, third terms.* Introduction to the tools and concepts of analytical political science. Subject matter is primarily American political processes and institutions. Topics: spatial models of voting, redistributive voting, games, presidential campaign strategy, Congress, congressional-bureaucratic relations, and coverage of political issues by the mass media. Instructors: Ordeshook, Kiewiet.

PS 97. Undergraduate Research. *Unites to be arranged; any term.Prerequisites: advanced political science and instructor's permission.* This courseoffers advanced undergraduates the opportunity to pursue research in political science individually or in a small group. Graded pass/fail.

PS 99 ab. Political Science Research Seminar. *9 units (3-0-6). Prerequisites: political science major; completion of a required PS course for major.* Development and presentation of a major research paper on a topic of interest in political science or political economy. The project will be one that the student has initiated in a political science course he or she has already taken from the PS courses required for the PS option, numbered above 101. This course will be devoted to understanding research in political science, and basic political science methodology. Students will be exposed to current research journals, work to understand a research literature of interest, and work to formulate a research project. *Fulfills the Institute scientific writing requirement.* Instructor: Ordeshook

PS 101. Selected Topics in Political Science. *Units to be determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

PS 120. American Electoral Behavior and Party Strategy. *9 units (3-0-6); third term.* A consideration of existing literature on the voting behavior of the citizen, and an examination of theoretical and empirical views of the strategies followed by the parties. Two substantial papers are expected of students. Instructor: Alvarez.

PS 121. Analyzing Congress. *9 units (3-0-6); fall term.* Introduction to the US Congress with an emphasis on thinking analytically and empirically about the determinants of Congressional behavior. Among the factors examined are the characteristics and incentives of legislators, rules governing the legislative process and internal organization, separation of powers, political parties, Congressional elections, and interest group influence. Instructor: Hirsch.

PS 122. Political Representation. *9 units (3-0-6); second term. Prerequisite: PS 12.* Theory, practice, and consequence of political representation in the electoral context. Topics include the concept of representation; how the degree of representation of various groups and interests (such as ethnic and racial) is affected by different electoral rules; and the impact of representation of minorities on public policies. The primary focus is on the empirical literature pertaining to the United States, but examples from other countries are also examined for comparative purposes. Not offered 2015–16.

PS 123. Regulation and Politics. *9 units (3-0-6); second term. Prerequisite: PS 12.* This course will examine the historical origins of several regulatory agencies and trace their development over the past century or so. It will also investigate a number of current issues in regulatory politics, including the great discrepancies that exist in the cost-effectiveness of different regulations, and the advent of more market-based approaches to regulations instead of traditional "command-and-control." Not offered on a pass/fail basis. Instructor: Kiewiet.

PS 124. Political Economy. *9 units (3-0-6); third term.* The aim of this course is to introduce students to theoretical and applied research in political economy. The focus will be on formal analysis of the strategic interaction between rational individuals, political institutions, and economic outcomes. Some of the questions will be: Why do people vote? What are the incentives of elected politicians, and what is the effect of these incentives on the policies they will implement? To what extent do differences in political institutions account for differences in redistributive policies? Topics may include the theory of voting, models of direct democracy, models of electoral competition, the political economy of redistribution, and comparative political institutions. Not offered 2015–16.

An/PS 127. Corruption. *9 units (3-0-6).* For course description, see Anthropology.

PS 130. Introduction to Social Science Surveys: Methods and Practice. *9 units (3-0-6); third term.* In this course, students will learn the basic methodologies behind social science survey analysis: self-completion and interview-assisted surveying, sampling theory, questionnaire design, theories of survey response, and the basic analysis and presentation of survey results will be covered, as well as contemporary research in survey methodology and public opinion analysis. Students will be involved in the active collection and analysis of survey data and the presentation of survey results; students will be required to complete an independent project involving some aspect of survey methodology. Not offered 2015–16.

PS 132. Formal Theories in Political Science. *9 units (3-0-6); first term. Prerequisite: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theoretic and social choice models and models of political processes based on them. Instructor: Agranov.

PS 135. Analyzing Legislative Elections. *9 units (3-0-6); second term.* The purpose of this course is to understand legislative elections. The course will study, for example, what role money plays in elections and why incumbents do better at the polls. It will also examine how electoral rules impact the behavior both of candidates and voters, and will explore some of the consequences of legislative elections, such as divided government. Instructor: Katz.

PS/SS 139. Comparative Politics. *9 units (3-0-6); second term. Prerequisites: PS 12.* The politics of non-American political systems with an emphasis on their electoral systems and methodologies for assessing their compliance with democratic standards. Students will be expected to develop data sets appropriate to analyzing elections in individual countries and offering an assessment of the pervasiveness of fraud in those elections. The student's grade will be determined by a final written report reporting the methodology and results of their analysis. Instructors: Ordeshook.

PS 141 ab. A History of Budgetary Politics in the United States. 9 *units (3-0-6); second, third terms.* This class will examine budgetary conflict at key junctures in U.S. history. Topics include the struggle to establish a viable fiscal system in the early days of the Republic, the ante bellum tariff, the "pension politics" of the post-Civil War era, the growth of the American welfare state, and the battle over tax and entitlement reform in the 1980s and 1990s. Instructors: Kiewiet.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3).* For course description, see Economics.

PS/Ec 172. Game Theory. *9 units (3-0-6); third term. Prerequisites: Ec 11 or PS 12* This course is an introduction to non-cooperative game theory, with applications to political science and economics. It covers the theories of normal-form games and extensive-form games, and introduces solutions concepts that are relevant for situations of complete and incomplete information. The basic theory of repeated games is introduced. Applications are to auction theory and asymmetric information in trading models, cheap talk and voting rules in congress, among many others. Instructor: Tamuz.

PSYCHOLOGY

Psy 15. Social Psychology. *9 units (3-0-6); third term.* The study of how people think about other people and behave toward or around others. Topics include attribution, social cognition, motivation and incentive, social influence, liking, stereotyping, deception, fairness and altruism, and conformity. Instructor: Awipi.

Psy 16. Understanding Psychological Disorders. *9 units (3-0-6); first term.* A descriptive and theoretical survey of the major forms of psychopathology in children, adolescents, and adults. The course will examine current trends and research in the fields of mental health and psychopathology. Instructor: Paul.

Psy 20. Introduction to Cognitive Psychology. *9 units (3-0-6); first term.* This course will develop basic concepts in how humans process different kinds of information such as visual, auditory, and symbolic. These concepts will then be used to explore topics such as visual perception, attention and automaticity, working and long-term memory, imagery, knowledge representation, language acquisition and comprehension, judgement and choice, reasoning and decision making, problem solving, and group differences. Instructor: Tudusciuc.

Psy 25. Reading and Research in Psychology. *Units to be determined by the instructor. Not available for credit toward humanities–social science requirement.* Written report required. Graded pass/fail. Not offered 2015–16.

Psy 101. Selected Topics in Psychology. *Units to be determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5); first term.* The new discipline of Neuroeconomics seeks to understand the mechanisms underlying human choice behavior, born out of a confluence of approaches derived from Psychology, Neuroscience and Economics. This seminar will consider a variety of emerging themes in this new field. Some of the topics we will address include the neural bases of reward and motivation, the neural representation of utility and risk, neural systems for intertemporal choice, goals vs habits, and strategic interactions. We will also spend time evaluating various forms of computational and theoretical models that underpin the field such as reinforcement-learning, Bayesian models and race to barrier models. Each week we will focus on key papers and/or book chapters illustrating the relevant concepts. Not offered 2015–16

Ec/Psy 109 ab. Frontiers in Behavioral Economics. *9 units (3-0-6). Prerequisites: Ec 11.* For course description, see Economics.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5-0-3.5).* For course description, see Computation and Neural Systems.

Psy 125. Reading and Research in Psychology. Same as Psy 25, but for graduate credit. *Not available for credit toward humanities–social science requirement.* Not offered 2015–16.

Psy/CNS 130. Introduction to Human Memory. *9 units (3-0-6); second term.* The course offers an overview of experimental findings and theoretical issues in the study of human memory. Topics include iconic and echoic memory, working memory, spatial memory, implicit learning and memory; forgetting: facts vs. skills, memory for faces; retrieval: recall vs. recognition, context-dependent memory, semantic memory, spreading activation models and connectionist networks, memory and emotion, infantile amnesia, memory development, and amnesia. Not offered 2015–16.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/Bi/SS/Psy/NB 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0); first, second, third terms.* For course description, see Social Science.

SOCIAL SCIENCE

SS 98. Reading in Social Science. *Units to be determined for the individual by the department. Elective, in any term.* Reading in social science and related subjects, done either in connection with the regular courses or independently of any course, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

SS 101. Selected Topics in Social Science. *Units to be determined by arrangement with the instructor; offered by announcement.* Not available for social science credit unless specifically approved by social science faculty. Instructors: Staff, visiting lecturers.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5-0-3.5).* For course description, see Computation and Neural Systems.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6).* For course description, see History.

Ec/SS 124. Identification Problems in the Social Sciences. *9 units (3-0-6); second term.* For course description, see Economics.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6); second term.* For course description, see Economics.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Twentieth Century. *9 units (3-0-6); third term.* For course description, see Economics.

PS/SS 139. Comparative Politics. *9 units (3-0-6); second term.* For course description, see Political Science.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6).* For course description, see Anthropology.

SS/CS 149. Introduction to Algorithmic Economics. *9 units (3-0-6); first term. Prerequisites: Ma 3, CS 24 and CS 38, or instructor permission.* This course will equip students to engage with current topics of active research at the intersection of social and information sciences, including: algorithmic mechanism design; auctions; existence and computation of equilibria; and learning and games. Not offered 2015–16.

CS/SS 152. Introduction to Data Privacy. *(3-0-6); First. Prerequisites: Ma 3, CS 24 and CS 38, or instructor's permission.* For course description, see Computer Science.

CNS/Bi/SS/Psy/NB 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

The graduate courses listed below are not necessarily taught each year. They will be offered as need dictates.

SS 200. Selected Topics in Social Science. *Units to be determined by arrangement with instructors; offered by announcement.* Instructors: Staff, visiting lecturers.

SS 201 abc. Analytical Foundations of Social Science. *9 units (3-0-6); first, second, third terms.* This course covers the fundamentals of utility theory, game theory, and social choice theory. These basic theories are developed and illustrated with applications to electoral politics, market trading, bargaining, auctions, mechanism design and implementation, legislative and parliamentary voting and organization, public economics, industrial organization, and other topics in economics and political science. Open to Social Science graduate students only. Instructors: Saito, Tamuz, Echenique.

SS 202 abc. Political Theory. *9 units (3-0-6); first, second, third terms.* Course will introduce the student to the central problems of political theory and analysis, beginning with the essential components of the democratic state and proceeding through a variety of empirical topics. These topics will include the analysis of electoral and legislative institutions, legislative agenda processes, voting behavior, comparative political economy, and cooperation and conflict in international politics. The student will be sensitized to the primary empirical problems of the discipline and trained in the most general applications of game theoretic reasoning to political science. Open to Social Science graduate students only. Instructors: Hirsch, Katz, Alvarez.

SS 205 abc. Foundations of Economics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ec 121 ab or instructor's permission.* This is a graduate course in the fundamentals of economics. Topics include comparative statics and maximization techniques, the neoclassical theory of consumption and production, general equilibrium theory and welfare economics, public goods and externalities, the economic consequences of asymmetric information and incomplete markets, and recursive methods with applications to labor economics and financial economics. Open to Social Science graduate students only. Instructors: Border, Echenique, Palfrey.

SS 209. Behavioral Economics. *9 units (3-0-6); spring term. Prerequisite: SS 201 abc or instructor's permission.* This course explores how psychological facts and constructs can be used to inform models of limits on rationality, willpower and greed, to expand the scope of economic analysis. Topics include overconfidence, heuristics for statistical judgment, loss-aversion, hyperbolic discounting, optimal firm behavior when consumers are limited in rationality, behavioral game theory, behavioral finance, neuroeconomic dual-self models, and legal and welfare implications of rationality limits. Not offered 2015–16.

SS 210 abc. Foundations of Political Economy. *9 units (3-0-6); first, second, third terms. Prerequisites: SS 202 c, SS 205 b.* Mathematical theories of individual and social choice applied to problems of welfare economics and political decision making as well as to the construction of political economic processes consistent with stipulated ethical postulates, political platform formulation, the theory of political coalitions, and decision making in political organizations. Instructor: Yariv.

SS 211 abc. Advanced Economic Theory. *9 units (3-0-6); first, second, third terms. May be repeated for credit.* Advanced work in a specialized area of economic theory, with topics varying from year to year according to the interests of students. Instructors: Saito, Yariv.

SS 212. Application of Microeconomic Theory. *9 units (3-0-6). May be repeated for credit.* A working seminar in which the tools of microeconomic theory are applied to the explanation of events and the evaluation of policy. Not offered 2015–16.

SS 213 abc. Financial Economics. *9 units (3-2-4); first, second, third terms.* First term: asset pricing theory, statistical tests on historical data and evidence from financial markets experiments. Second term: financial econometrics, with emphasis on applications to risk management. Third term: general equilibrium foundations of asset and option pricing theory. Not offered 2015–16.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6); first term.* A course on pricing financial derivatives, risk management, and optimal portfolio selection using mathematical models. Students will be introduced to methods of Stochastic, Ito Calculus for models driven by Brownian motion. Models with jumps will also be discussed. Instructors: Cvitanic.

SS 215. Asset Pricing Theory. *9 units (3-0-6); third term. Prerequisites: Students are recommended (but not required) to take SS/Ma 214.* This course is designed to get students familiar with modern research in asset pricing theory. It covers topics like arbitrage and pricing, mean-variance single period problem, arbitrage pricing theory, basics of continuous-time finance, valuation of assets in continuous-time and risk-neutral pricing, term structure results and considerations, intertemporal consumption-based asset pricing models, information economics, and some recent development in intermediary-based asset pricing models and behavioral asset pricing models. Instructors: Jin.

SS 216. Interdisciplinary Studies in Law and Social Policy. *9 units (3-0-6); second term.* A policy problem or problems involving the legal system will be studied, using concepts from at least one social science discipline.

Each offering will be taught by a law professor, alone or in conjunction with a member of the social science faculty. The topic will differ from term to term, so the course may be taken more than once. Selected undergraduates may enroll in this course with the permission of the instructor. Not offered 2015–16.

SS 218. Neuroscience Applications to Economics and Politics. *9 units (3-0-6); third term.* Topics in behavioral, affective, and social neuroscience that inform how individuals make economic decisions. Applications of neuroscience to understanding choice under risk and uncertainty, temporal discounting and self-control, advertisement and preference formation, addiction and other pathological behaviors, experienced utility, empathy, and trust. Not offered 2015–16.

SS 222 abc. Econometrics. *9 units (3-0-6); first, second, third terms.* Introduction to the use of multivariate and nonlinear methods in the social sciences. Open to Social Science graduate students only. Instructor: Shum, Gillen, Sherman.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: SS 222 abc; may be repeated for credit.* A course in quantitative methods for second- and third-year social science graduate students. Instructor: Sherman.

SS 225. Experimetrics. *9 units (3-0-6); first term.* This course explores the interaction of experimental design and econometric inference in the laboratory approach to economic questions. The course critically evaluates existing experimental studies to highlight this interaction and motivate consideration of inferential strategies early in an experiments design. Methodological topics may include testing theories in two-by-two designs, power and optimal design, classifying subjects into canonical types, testing based on elicited preferences and beliefs, and challenges introduced by communication and dynamics in economic experiments. Instructors: Agranov, Gillen.

SS 227. Empirical Methods in the Social Sciences. *9 units (3-0-6), second term. Prerequisites: SS 222 abc.* There is a tension in modeling social science phenomena between making strong assumptions, which lead to descriptive or normative conclusions that are precise when the assumptions hold but invalid when they do not hold, and making weak assumptions, which lead to less precise conclusions but hold more generally. The preponderance of social science research to date takes the former approach. This course studies recent advances in the latter approach. The course will review the work of Manski on bounds identification and estimation and trace some of the developments in this line of research to the present. Various applications of the methodology will be considered, including applications to Stanford-9 test-score data and data on organic pollutants in the Love Canal. Instructor: Ewens.

SS 228. Applied Data Analysis for the Social Sciences. *9 units (3-0-6); third term.* The course covers issues of management and computation in the statistical analysis of large social science databases. Maximum likelihood and Bayesian estimation will be the focus. This includes a study of Markov Chain Monte Carlo (MCMC) methods. Substantive social science problems will be addressed by integrating programming, numerical optimization, and statistical methodology. Not offered 2015–16.

SS 229 abc. Theoretical and Quantitative Dimensions of Historical Development. *9 units (3-0-6); first, second terms. May be repeated for credit.* Introduction to modern quantitative history. The tools of economic and political theory applied to problems of economic, social, and political development in a historical context. Second and third terms will be graded together. A pass/fail will be assigned in the second term and then changed to the appropriate letter grade at the end of the third term. Instructor: Rosenthal, Hoffman.

SS 231 abc. American Politics. *9 units (3-0-6); first, second, third terms.* A three-term course in American politics and political behavior. While drawing from con temporary materials, the course will emphasize the historical background of American political institutions. Instructor: Alvarez.

SS 232 abc. Historical and Comparative Perspectives in Political Analysis. *9 units (3-0-6); second term.* Provides a knowledge and understanding of developments in both the American past and in other parts of the world. Not offered 2015–16.

SS 240. Techniques of Policy Research. *9 units (3-0-6). Prerequisite: SS 205 ab.* The application of social science theory and methods to the formulation and evaluation of public policy. Not offered 2015–16.

SS/CS 241. Topics in Algorithmic Economics. *9 units (3-0-6). Prerequisites: SS/CS 149.* This is a graduate-level seminar covering recent topics at the intersection of computer science and economics. Topics will vary, but may include, e.g., dynamics in games, algorithmic mechanism design, and prediction markets. Instructors: EAS and HSS faculty. Not offered 2015–16.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (2-1-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6); third term. Prerequisite: Bi/CNS/NB 150 or instructor's permission.* This course will cover recent findings in the psychology and neurobiology of emotion and social behavior. What role does emotion play in other cognitive processes, such as memory, attention, and decision making? What are the component processes that guide social behavior? To what extent is the processing of social information domain-specific? Readings from the current literature will emphasize functional imaging, psychophysical, and lesion studies in humans. Not offered 2015–16.

SS 260. Experimental Methods of Political Economy. *9 units (3-3-3); first, second, third terms.* Survey of laboratory experimental research related to the broad field of political economy. Topics: the behavior of markets, organizations, committee processes, and election processes. Emphasis on experimental methods and techniques. Students will design and conduct experiments. May be repeated for credit with instructor's permission. Instructor: Plott.

SS 281. Graduate Social Science Writing Seminar. *9 units (3-0-6); third term.* Only open to advanced graduate students in social science. How can social scientists write in a style that makes someone actually want to read their papers? This seminar combines writing exercises with help in planning a professional social science paper and with extensive comments on drafts. Not offered 2015–16.

SS 282 abc. Graduate Proseminar in Social Science. *3 units (2-0-1); first, second, third terms.* Course for graduate students in social sciences. Students present their research and lead discussion of material relevant to their research program. Open to Social Science Graduate Students only. Instructor: Echenique.

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0); first, second, third terms.* Select faculty will present their research background, methods, and a sampling of current questions/studies. Background readings and pdf of presentation will be provided. Instructors: Adolphs, Alvarez.

SS 300. Research in Social Science. *Units to be arranged.*

WRITING

Wr 1. Introduction to Academic Writing for Multilingual Writers. *9 units (3-0-6); first term.* This course offers a focused introduction to the practices of reading, thinking, and writing that characterize academic writing. More specifically, the course teaches students how to articulate a position, situate writing within specific contexts, engage with the work of others, locate and provide convincing evidence, and understand the expectations of different types of academic readers. Additionally, this course focuses on the challenges of academic writing that can be especially demanding for multilingual writers, including mastery of Academic English, understanding American academic conventions regarding citation and plagiarism, and being comfortable with American academic readers' expectations regarding argumentation and evidence. Students will take several writing projects through multiple stages of revision, improving their work with feedback from seminar discussions, workshops, and frequent one-to-one conferences with the instructor. Students are placed in Wr 1 based on a writing assessment that is required of all incoming students; successful completion of the course is required before taking freshman humanities courses. Enrolled students may be required to take Wr 3, 4, and/or 50 in subsequent quarters. Instructors: Hall, S.

Wr 2. Introduction to Academic Writing. *9 units (3-0-6); first term.* This course offers a focused introduction to the practices of reading, thinking, and writing that characterize academic writing. More specifically, the course teaches students how to articulate a position, situate writing within specific contexts, engage with the work of others, locate and provide convincing evidence, and understand the expectations of different types of academic readers. Students will take several writing projects through multiple stages of revision, improving their work with feedback from seminar discussions, workshops, and frequent one-to-one conferences with the instructor. Students are placed in Wr 2 based on a writing assessment that is required of all incoming students; successful completion of the course is required before taking freshman humanities courses. Enrolled students may be required to take Wr 3, 4, and/or 50 in subsequent quarters. Instructors: Daley.

Wr 3. Reading and Composing Academic Writing. *9 units (3-0-6); second term.* This course builds on Wr 1 or 2 for students who need additional instruction in both the core concepts and practices of academic writing before beginning their freshman humanities coursework. The course will focus on developing critical reading skills and composing successful academic essays. By taking several writing projects through multiple stages of revision, students will develop a deeper sense of their strengths and limitations as writers, and seminar discussions, workshops, and frequent one-to-one conferences with the instructor will equip students to address those limitations. Not available for credit toward the humanities-social science requirement. Enrolled students may be required to take Wr 4 and/or 50 in subsequent quarters. Instructors: Hall, S.

Wr 4. Principles and Practices of Academic Writing. *3 units (1-0-2); second term.* Taken simultaneously with a freshman humanities course, this course offers weekly discussion of core concepts in academic writing. By focusing on the diverse scenes, situations, and genres of academic writing, the course aims to support writers both in their concurrent work writing in humanistic disciplines and to connect that learning to writing tasks that students will encounter in other academic locations. Not available for credit toward the humanities-social science requirement. Enrolled students also take Wr 50. Instructors: Hall, S.

Wr 50. Tutorial in Writing. *1-3 units to be arranged. By permission only.* Individualized tutorial instruction in writing and communication for students who benefit from weekly discussions about their work as writers. Not available for credit toward the humanities-social science requirement. Instructors: Hall, S.

En/Wr 84. Writing About Science. *9 units (3-0-6); third term.* For course description, see English.

Trustees, Administration, Faculty

OFFICERS

David L. Lee, *Chairman*
Ronald K. Linde, *Vice Chairman*

Thomas F. Rosenbaum, *President*
Edward M. Stolper, *Provost*

Matthew Brewer
Controller
Dean W. Currie
Vice President for Business and Finance
Charles Elachi
Vice President and Director, Jet Propulsion Laboratory
Diana Jergovic
Vice President for Strategic Implementation
Brian K. Lee
Vice President for Development and Institute Relations
Sharon E. Patterson
Associate Vice President for Finance and Treasurer
Scott Richland
Chief Investment Officer
Joseph E. Shepherd
Vice President for Student Affairs
Victoria D. Stratman
General Counsel
Mary L. Webster
Secretary

BOARD OF TRUSTEES

Trustees
(with date of first election)

S. R. Onderdonk, T. F. Rosenbaum*, L. W. van Amerongen; *Consulting Member:* S. D. Bechtel Jr.; *Advisory Members:* J. W. Cowell, D. W. Currie, H. P. Daily, D. Jergovic, B. K. Lee, S. H. Richland, A. I. Sargent, E. M. Stolper

Business and Finance Committee—P. D. Kaufman, *Vice Chair;* B. M. Bren, T. E. Everhart, G. B. Jones, K. Kresa, D. L. Lee*, A. Lidow, R. K. Linde, A. M. Lipper, A. N. Liveris, S. M. Malcom, D. D. McWhinney, K. G. Moore, P. M. Neches, T. F. Rosenbaum*, D. W. Tang, L. W. van Amerongen, W. L. Weisman, R. A. Wolf, S. H. Woolsey; *Consulting Member:* H. M. Conger; *Advisory Members:* D. W. Currie, D. Jergovic, B. K. Lee, J. M. McCallin, S. E. Patterson, S. L. Proia, S. H. Richland, E. M. Stolper, V. D. Stratman

Development Committee—W. H. Davidow, *Chair;* David T. Dreier, *Vice Chair;* L. A. Booth, J. E. Bryson, M. D. Hummer-Tuttle, R. T. Jenkins, P. D. Kaufmann, K. Kresa, D. L. Lee*, D. D. McWhinney, T. F. Rosenbaum*, W. L. Weisman; *Advisory Members:* D. M. Binney, D. Gastevich, D. Jergovic, B. K. Lee, V. A. Otten, S. H. Richland, E. M. Stolper

Executive Compensation Committee—R. K. Linde, *Chair;* A. Lidow, *Vice Chair*; D. L. Lee*, P. M. Neches, W. L. Weisman; *Advisory Members:* J. M. McCallin, T. F. Rosenbaum

Institute and Alumni Relations Committee—S. M. Malcom, *Chair;* D. T. Dreier, *Vice Chair*, M. M. Chang, W. H. Davidow, L. M. Dyer, W. T. Gross, R. T. Jenkins, L. Kirkbride, D. L. Lee*, P. M. Neches, S. R. Onderdonk, T. F. Rosenbaum*; *Advisory Members:* D. M. Binney, D. W. Currie, H. P. Daily, D. Gastevich, D. Jergovic, B. K. Lee, V. A. Otten, A. I. Sargent, E. M. Stolper; *Ex Officio Standing Attendees:* Alumni Association President, Alumni Fund Chair, The Associates President, Faculty Chair

Investment Committee—J. S. Friedman, *Chair;* R. K. Linde, *Vice Chair;* B. K. Hagopian, D. L. Lee*, A. M. Lipper, S. A. Ross, T. F. Rosenbaum*; *Advisory Members:* D. W. Currie, S. Dow, L. Lu, S. H. Richland, R. P. Spogli, E.M. Stolper

Jet Propulsion Laboratory Committee—J. B. Kutler, *Chair;* B. M. Barrett, *Vice Chair;* R. C. Bonner, D. T. Dreier, L. M. Dyer, T. E. Everhart, J. S. Friedman, F. J. Hameetman, S. M. Hufstedler, B. R. Inman, L. Kirkbride, D. L. Lee*, D. D. McWhinney, R. N. Merkin, P. M. Neches, P. Norton, R. L. Olson, S. R. Onderdonk, S. A. Resnick, T. F. Rosenbaum*, C. R. Trimble, W. L. Weisman, G. E. Wilson, S. H. Woolsey; *Consulting Members:* H. Brown, G. E. Moore; *Advisory Members:* D. W. Currie, H. P. Daily, C. Elachi, L. D. James, D. Jergovic, B. K. Lee, J. T. Lum, R. P. O'Toole, E. M. Stolper, V. D. Stratman,

Governance Subcommittee [A subcommittee of the JPL Committee]—J. B. Kutler, *Chair ex officio*; B. M. Barrett*, R. C. Bonner, *, B. R. Inman, K. Kresa, D. L. Lee*, T. F. Rosenbaum*; *Advisory Members:* D. W. Currie, C. Elachi, L. D. James, P. D. Koyzis, E. M. Stolper, V. D. Stratman

Nominating Committee—B. M. Bren, *Chair;* A. Lidow, *Vice Chair;* L. A. Booth, J. S. Chen, N. K. Gupta, M. D. Hummer-Tuttle, B. R. Inman, L. Kirkbride, D. L. Lee*, R. K. Linde, D. D. McWhinney, R. N. Merkin, R. L. Olson, T. F. Rosenbaum*, M. I. Stern, D. W. Tang, W. L. Weisman, G. E. Wilson, S. H. Woolsey; *Consulting Members:* S. Ramo, V. V. Weldon; *Advisory Members:* D. Jergovic, B. K. Lee, E. M. Stolper, V. D. Stratman

Student Experience Committee—P. M. Neches, *Chair;* D. D. McWhinney, *Vice Chair*, J. E. Bryson, M. M. Chang, R. B. Chess, L. M. Dyer, R. T. Jenkins, L. Kirkbride, D. L. Lee*, Y. Liao, S. M. Malcom; P. H. Nettles Jr., P. Norton, T. F. Rosenbaum*, R. H. Scheller, D. W. Thompson, C. R. Trimble, S. H. Woolsey; *Consulting Member:* V. V. Weldon; *Advisory Members:* D. Jergovic, B. K. Lee, A. I. Sargent, J. E. Shepherd, E. M. Stolper, C. A. Weinstein; *Student Advisory Members:* E. Blythe, B. Lepe, M. Post, M. J. Sonola

Technology Transfer Committee—R. B. Chess, *Chair,* R. A. Wolf, *Vice Chair;*

** ex officio member*

M. M. Chang, W. Chen, P. T. Cherng, L. M. Dyer, N. K. Gupta, B. K. Hagopian, R. T. Jenkins, L. Kirkbride, J. B. Kutler, D. L. Lee*, Y. Liao, P. M. Neches, P. H. Nettles Jr., P. Norton, S. A. Resnick, T. F. Rosenbaum*, R. H. Scheller, D. W. Tang, K. M. Taweel, C. R. Trimble, L. W. van Amerongen; *Consulting Members:* H. Brown, A. L. Goldstein; *Advisory Members:* D. W. Currie, F. Farina, M. Gharib, D. Jergovic, B. K. Lee, S. H. Richland, E. M. Stolper, V. D. Stratman

** ex officio member*

ADMINISTRATIVE OFFICERS

Thomas F. Rosenbaum
President

Edward M. Stolper
Provost

Dean W. Currie
Vice President for Business and Finance
John O. Dabiri
Dean of Students
Hall P. Daily
Director of Government Relations
Charles Elachi
Vice President and Director, Jet Propulsion Laboratory
Richard E. Fagen
Chief Information Officer
Morteza Gharib
Vice Provost
Richard F. Flagan
Chair of the Faculty
Diana Jergovic
Vice President for Strategy Implementation
Brian K. Lee
Vice President for Development and Institute Relations
Julia McCallin
Associate Vice President for Human Resources

Sharon E. Patterson
Associate Vice President for Finance and Treasurer
Douglas C. Rees
Dean of Graduate Studies
Scott Richland
Chief Investment Officer
Joseph E. Shepherd
Vice President for Student Affairs
Victoria D. Stratman
General Counsel
Mary L. Webster
Secretary, Board of Trustees
Cindy A. Weinstein
Vice Provost

Chairs of Divisions
Stephen L. Mayo
Biology
Jacqueline K. Barton
Chemistry and Chemical Engineering
Fiona A. Harrison
Physics, Mathematics and Astronomy
Ares J. Rosakis
Engineering and Applied Science
John P. Grotzinger
Geological and Planetary Sciences
Jean-Laurent Rosenthal
Humanities and Social Sciences

Administrative Committees

Animal Care and Use [fills the role of Caltech's Institutional Animal Care and Use Committee—IACUC] (Reports to the Vice Provost for Research)—H. A. Lester, chair, R. A. Andersen, vice chair; J. Baer*, J. Brackman, O. Caglar* (alternate), D. C. Chan, C. M. d'Apuzzo*, P. Dervan (alternate), K. Gilbert (alternate) L. C. Hsieh-Wilson, K. Lencioni* (alternate), D. J. Mayo*, C. Scislowicz*, C. Zuffada*

Benefits (Reports to the Vice President for Business and Finance)—D. M. Grether, *Chair*; A. Boladian, K. Bradshaw, D. W. Currie*, D. Dougherty, C. Hart*, P. T. Hoffman, M. Jaross*, P. C. Jennings, J. McCallin*, J. C. Milbrandt, S. E. Patterson*, M. Powell-Meeks, S. Proia, R. M. Roessler*, S. Scoville*, J. Stock, O. Velazquez-Perez

Biosafety [fills the role of Caltech's Institutional Biosafety Commit-tee—IBC] (Reports to the Vice Provost for Research)—J. Leadbetter, *Chair*; J. Baer*, S. Chatterjee, C. Cortese, C. M. d-Apuzzo*, W. Dietrick, G. Fisher-Adams*, K. Gilbert*, R. Ismagilov, S. Mazmanian, C. Scislowicz*, R. P. Seligman*

Computing Advisory Committee (Reports to the Provost and the Vice President for Business and Finance)—B. Fultz, *Chair;* N. D. Badizadegan *(representing undergraduate students)* R. W. Clayton, R. E. Fagen, P. E. Hopkins, G. J. Jensen, A. Jermyn‡, J. T. Kaiser§, Y. P. Leong *(representing graduate students)*, J. McCallin*, B. V. McKoy, S. Patterson, A. T. Ryan *(representing undergraduate students),* M. S. Shum, B. M. Simon

Council on Undergraduate Education (Reports to the Provost)—C. A. Weinstein, *Chair;* P. M. Bellan, J. O. Dabiri, J. F. Hall, C. Jurca, K. L. Libbrecht, M. N. Morley, A. I. Sargent, J. M. Stock, B. M. Stoltz

Environmnental Health and Safety (Reports to the President)—E. M. Stolper, *Chair;* J. W. Cowell*, D. W. Currie, A. I. Sargent, C. Scislowicz*

Institute Academic Council (IACC)—E. M. Stolper, *Chair*; J. K. Barton, J. P. Grotzinger, F. Harrison, S. L. Mayo, A. J. Rosakis, T. F. Rosenbaum, J-L Rosenthal

Institute Administrative Council (IAC)—T. F. Rosenbaum, *Chair*; J. K. Barton, J. W. Cowell, D. W. Currie, J. O. Dabiri, H. P. Daily, C. Elachi, R. Fagen, R. Flagan, D. Gastevich, M. Gharib, J. P. Grotzinger, F. Harrison, D. Jergovic, B. K. Lee, J. Lum, S. L. Mayo, J. McCallin, S. Patterson, S. Richland, A. J. Rosakis, J-L Rosenthal, R.

P. Seligman, J. E. Shepherd, E . M. Stolper, V. D. Stratman, M. L. Webster, C. A. Weinstein

Institute Art (Reports to the Assistant Vice President for Campus and Community Relations)—P. Perona, *Chair*; A. Boyle, J. Buchwald, F. E. C. Culick, H. P. Daily, G. Gage, C. Klein‡, T. Knutson†, D. Kremers, T. Schneider, C. S. Smith, C. Theodoris‡ (alternate), L. Yeung†

Protection of Human Subjects [fills the role of Caltech's Institutional Review Board—IRB] (Reports to the Vice Provost for Research)—R. Adolphs, *Chair;* R. Andersen, *vice chair*, J. Baer, M. E. Csete, C. M. d-Apuzzo*, R. I. Feinberg, M. Gibson, J. L. Kirschvink, P. Perona, K. Reimer, C. Scislowicz*, R. Seligman*, J. M. Tyszka*, K. K. Wong Jr., C. Zuffada

Radiation Safety (Reports to the Vice President for Business and Finance)—D. S. Burnett, *Chair*; B. Filippone, H. Issaian, W. L. Johnson, A. Kumagai, C. Scislowicz*, S. Shan

Sponsored Research (Reports to the Provost)—B. V. McKoy, *Chair*; P. M. Bellan, T. H. Heaton, J. O. Ledyard, R. P. Seligman*, N. C. Yeh

SURF (Reports to the Provost)—J. Jackson, *Chair*; G. A. Blake*, G. Blanquart, D. Crewel*, J. O. Dabiri, B. J. Gillen, M. Gonzalez*, D. D. Hall*, E. Mantovan, G. Orton, A. Ponce*, C. Rypisi*, A. Stathopoulos, Z-G Wang, R. M. Wilson

** ex officio member*
† representing graduate students
‡ representing undergraduate students
§ representing postdoctoral scholars

FACULTY OFFICERS AND COMMITTEES 2015–16

Officers

Chair: R. C. Flagan
Vice Chair: M. B. Kennedy
Secretary: K. L. Haugen

Faculty Board

K. Bhattacharya, 2017
G. A. Blake, 2018
W. M. Clemons, 2018
M. Desbrun, 2018
S. G. Djorgovski , 2017
B. W. Filippone, 2017
S. A. Hajimiri, 2018
A. P. Ingersoll, 2017
H. A. Lester, 2017
E. Mantovan, 2016
T. F. Miller, 2016
M. Ortiz, 2016
M. Spiropulu, 2016
A. Stathopoulos, 2017
P. W. Sternberg , 2016
J. A. Tropp, 2018
P. O. Wennberg, 2018
L. Yariv, 2016

Ex Officio:
J. K. Barton
J. P. Grotzinger
F. A. Harrison
S. L. Mayo
D. C. Rees
A. J. Rosakis
T. F. Rosenbaum
J. -L. Rosenthal
J. E. Shepherd
E. M. Stolper

Steering

R. C. Flagan, *Chair*
K. Bhattacharya
M. Gharib
K. L. Haugen
A. P. Ingersoll
M. B. Kennedy
T. F. Miller
P. W. Sternberg
E. M. Stolper
C.A. Weinstein

Academic Freedom and Tenure
H. A. Lester, *Chair*
K. A. Farley, 2017
L. Hillenbrand, 2017
R. M. Murray, 2017
D. B. Rutledge, 2016
D. A. Tirrell, 2016

Academic Policies
C. R. Hitchcock, *Chair*
B. Hassibi, 2018
M. B. Kennedy, 2017
J. Pine, 2017
A. L. Sessions, 2017
M. Spiropulu, 2016

Athletics and Physical Education
T. K. Dennison, *Chair*
B. W. Filiponne, 2017
M. R. Hoffmann, 2017
J. L. Kirschvink, 2016
B. Mitchell*
A. G. Siapas, 2018
B. M. Stoltz, 2018
J. Trosper, 2016
J. Whitney*

Convocations
W. C. Brown, *Chair*
M. B. Kennedy*
D. Prober, 2016
D. C. Rees*
P. Schroeder, 2016
L. Yariv, 2016
N. C. Yeh, 2017

Core Curriculum Steering
J. F. Hall, *Chair*
M. Flach, 2017
P. T. Hoffman, 2017
M. L. Hunt, 2018
C. Jurca, 2017
M. N. Morley*
M. Okumura, 2017
R. B. Patterson, 2018
B. M. Stoltz, 2017
J. A. Tropp, 2016
K. G. Zinn, 2016

Curriculum
A. J. Weinstein, *Chair*
R. W. Clayton, 2018
K. Gilmartin, 2017
G. J. Jensen, 2017
M. N. Morley*
E. S. Phinney, 2016
D. C. Rees, 2017
P. Schroeder, 2017

Exchange Programs and Study Abroad (CEPSA)
H. B. Newman, *Chair*
T. Agapie, 2018
J. P. Ampuero Saenz, 2018
M. Bronner, 2017
M. Desbrun, 2016
A. Emami, 2017
J. R. Goodstein (non-voting)
M. N. Morley*
J. P. O'Doherty, 2016
L. Stolper*
A. F. Thompson, 2018

Foreign Students and Scholars
Z. G. Wang, *Chair*
D. Asimaki, 2018
S. Bordoni, 2016
G. W. Hallinan, 2018
A. Hoelz, 2016
A. Rangel, 2017
A. G. Siapas, 2017
I. Smith*

Freshman Admissions
J. Stock, *Chair*
M. Aschbacher, 2016
P. D. Asimow, 2017
J. L. Beauchamp, 2017
J. Cvitanic, 2016
D. Gilmore, 2018
N. H. Katz, 2017
K.G. Libbrecht, 2017
S. R. Quartz, 2016
J. H. Schwarz, 2016
S. Shimojo, 2017
D. J. Stevenson, 2018
C. M. Umans, 2018
J. Whitney*

Graduate Studies
C. Umans, *Chair**
J. E. Andrade*
R. W. Clayton*
W. M. Clemons*
A. Emami*

B. Fultz
K. P. Giapis*
T. B. Graber*
B. A. Hay*
L. Hillenbrand*
Y. T. Hou*
B. J. McKeon*
M. Meister*
R. M. Murray*
M. Okumura*
O. J. Painter
F. C. Porter*
D. C. Rees*
M. S. Shum*
A. G. Siapas*
A. F. Thompson*
A. C. Weirman
**ex officio member*

Health
C. Yang, *Chair*
C. C. Ahn, 2016
K. Austin*
F. Eberhardt, 2017
S. Golwala, 2018
H. A. Lester, 2016
S. C. Miller*
B. Mitchell*
N. A. Pierce, 2016
D. C. Rees*

Institute Programs
J. R. Greer, *Chair*
B. Brophy*
C. J. Hunter, 2016
A. P. Ingersoll, 2016
J. M. Jackson, 2016
B. K. Lee*
C. D. Ott, 2017
Z. G. Wang, 2018

Library
P.W. Sternberg, *Chair*
K. Antelman*
B. L. Ehlmann, 2018
T. B. Graber, 2018
A. N. Kapustin, 2016
G. W. Pigman, 2016
S. E. Reisman, 2017
G. Rossman, 2018
K. C. Schwab, 2018
V. C. Tsai, 2017

Membership and Bylaws
M. B. Kennedy, *Chair*
K. L. Haugen*
K. C. Border, 2016
M. Bronner, 2016
N. S. Lewis, 2016
E. Mantovan, 2016
R. M. Murray, 2016

Nominating
A. P. Ingersoll, *Chair*
K. Bhattacharya, 2016
S. G. Djorgovski, 2016
K. M. Gilmartin, 2016
E. Meyerowitz, 2016
S. E. Reisman, 2016

Patents and Relations with Industry
S. H. Low, Chair
R. J. Deshaies, 2016
K. P. Giapis, 2016
R. F. Ismagilov, 2018
N. A. Pierce, 2017
M. L. Roukes, 2018
K. J. Vahala, 2017

Scholarships and Financial Aid
G. Refael
D. Crewell*
F. Eberhardt, 2018
D. M. Kochmann, 2017
C. S. Parker, 2018
S. Shimojo, 2016
J. M. Stock*
J. Whitney*

Student Life and Housing
P. D. Asimow, *Chair*
A. Aravin, 2017
W. M. Clemons, 2016
J. G. Cohen, 2018
K. A. Ligett, 2017
T. Mannion (non-voting)
B. Mitchell*
D. C. Rees*
E. Snowberg*
V. C. Tsai, 2017

Undergraduate Academic Standards and Honors
D. P. Weitekamp, Chair
J. P. Ampuero Saenz, 2016
P. M. Bellan, 2016

J. F. Brady, 2016
W. C. Brown, 2017
M. H. Dickinson, 2018
J. E. Ensminger, 2016
J. R. Greer, 2016
J. R. Heath, 2018
E. Mantovan, 2016
M. N. Morley*
F. C. Porter, 2018

Upperclass Admissions
R. M. Murray, Chair
D. Asimaki, 2017
M. Effros, 2016
T. B. Graber, 2016
M. Guttman, 2018
J. A. Jahner, 2016
M. P. Lamb, 2016
T. F. Miller, 2016
M. N. Morley*
J. Whitney*

**ex officio member*

STAFF OF INSTRUCTION AND RESEARCH

Division of Biology and Biological Engineering

Stephen L. Mayo, *William K. Bowes Jr. Leadership Chair*
Raymond Deshaies, *Executive Officer for Molecular Biology*
Marianne Bronner, *Executive Officer for Neurobiology*
Michael Elowitz, *Executive Officer for Biological Engineering*

Professors Emeriti

John N. Abelson, Ph.D.
George Beadle Professor of Biology
Charles J. Brokaw, Ph.D.
Biology
John J. Hopfield, Ph.D.
Roscoe G. Dickinson Professor of Chemistry and Biology
Masakazu Konishi
Bing Professor of Behvioral Biology
Jean-Paul Revel, Ph.D.
Albert Billings Ruddock Professor of Biology
Melvin I. Simon, Ph.D.
Anne P. and Benjamin F. Biaggini Professor of Biological Sciences
James H. Strauss, Ph.D.
Ethel Wilson Bowles and Robert Bowles Professor of Biology

Senior Research Associate Emeriti

Anne Chomyn, Ph.D.
Ellen G. Strauss, Ph.D.

Professors

Ralph Adolphs, Ph.D.
Bren Professor of Psychology and Neuroscience and Professor of Biology
John M. Allman, Ph.D.
Frank P. Hixon Professor of Neurobiology
Richard A. Andersen, Ph.D.
James G. Boswell Professor of Neuroscience
David J. Anderson, Ph.D.[1]
Seymour Benzer Professor of Biology
Frances H. Arnold, Ph.D.
Dick and Barbara Dickinson Professor of Chemical Engineering, Bioengineering, and Biochemistry; Director, Donna and Benjamin M. Rosen Bioengineering Center
David Baltimore, Ph.D., D.Sc.h.c., D.Phil.h.c., Nobel Laureate
Robert Andrews Millikan Professor of Biology
Pamela Bjorkman, Ph.D.
Centennial Professor of Chemistry
Marianne Bronner, Ph.D.
Albert Billings Ruddock Professor of Biology; Executive Officer for Neurobiology
Judith L. Campbell, Ph.D.
Chemistry and Biology
David C. Chan, M.D., Ph.D.
Biology
John O. Dabiri, Ph.D.
Professor of Aeronautics and Bioengineering
Eric H. Davidson, Ph.D.
Norman Chandler Professor of Cell Biology
Raymond Deshaies, Ph.D.[1]
Biology; Executive Officer for Molecular Biology
Michael H. Dickinson, Ph.D.
Esther M. and Abe M. Zarem Professor of Bioengineering
William G. Dunphy, Ph.D.
Grace C. Steele Professor of Biology
Michael Elowitz, Ph.D.[1]
Biology and Bioengineering; Executive Officer for Biological Engineering
Morteza Gharib, Ph.D.
Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Vice Provost
Bruce A. Hay, Ph.D.
Biology
Rustim F. Ismagilov, Ph.D.
Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering; Director of the Jacobs Institute for Molecular Engineering for Medicine
Grant J. Jensen, Ph.D.[1]
Biophysics and Biology

[1] *Joint appointment with Howard Hughes Medical Institute*

Mary B. Kennedy, Ph.D.
Allen and Lenabelle Davis Professor of Biology
Henry A. Lester, Ph.D.
Bren Professor of Biology
Stephen L. Mayo, Ph.D.
Bren Professor of Biology and Chemistry; William K. Bowes Jr. Leadership Chair, Division of Biology and Biological Engineering
Sarkis Mazmanian, Ph.D.
Luis B. and Nelly Soux Professor of Microbiology
Markus Meister, Ph.D.
Anne P. and Benjamin F. Biaggini Professor of Biological Sciences
Elliot M. Meyerowitz, Ph.D.
George W. Beadle Professor of Biology
Richard Murray, Ph.D.
Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering
Dianne K. Newman, Ph.D.[1]
Biology and Geobiology
Robert B. Phillips, Ph.D.
Fred and Nancy Morris Professor of Biophysics and Biology
Niles A. Pierce, Ph.D.
Professor of Applied and Computational Mathematics and Bioengineering
Ellen Rothenberg, Ph.D.
Albert Billings Ruddock Professor of Biology
Michael L. Roukes, Ph.D.
Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering
Shinsuke Shimojo, Ph.D.
Gertrude Baltimore Professor of Experimental Psychology
Athanassios G. Siapas, Ph.D.
Computation and Neural Systems
Angelike Stathopoulos, Ph.D.
Biology
Paul W. Sternberg, Ph.D.[1]
Thomas Hunt Morgan Professor of Biology
Doris Ying Tsao, Ph.D.[1]
Biology
Alexander J. Varshavsky, Ph.D.
Howard and Gwen Laurie Smits Professor of Cell Biology
Erik Winfree, Ph.D.
Professor of Computer Science, Computation and Neural Systems, and Bioengineering
Barbara J. Wold, Ph.D.
Bren Professor of Molecular Biology
Changhuei Yang, Ph.D.
Professor of Electrical Engineering, Bioengineering, and Medical Engineering
Kai Zinn, Ph.D.
Biology

Assistant Professors

Alexei A. Aravin, Ph.D.
Biology
Lea Goentoro, Ph.D.
Biology
Viviana Gradinaru, Ph.D.
Biology and Biological Engineering
Mitchell Guttman, Ph.D.
Biology
Elizabeth J. Hong, Ph.D.
Neuroscience
Yuki Oka, Ph.D.
Biology
David Prober, Ph.D.
Biology
Lulu Qian, Ph.D.
Bioengineering

[1] *Joint appointment with Howard Hughes Medical Institute*

Senior Research Associate Emeriti

Anne Chomyn, Ph.D.
Ellen G. Strauss, Ph.D.
R. Andrew Cameron, Ph.D.

Lecturers

L. Elizabeth Bertani, Ph.D.
Justin Bois, Ph.D.
Lindsay Bremner, Ph.D.
Andres Collazo, Ph.D.
Alexandre Cunha, Ph.D.
Ciro Donelak, Ph.D.
Santiago V. Lombeyd, Ph.D.
Danny Petrasek, Ph.D.
Andrew Steele, Ph.D.
Carol Chace Tydell, DVM

Research Professors

Akiko Kumagai, Ph.D.
Carlos Lois, M.D., Ph.D.
Mary An-yuan Yui, Ph.D.

Research Assistant Professors
Katalin Fejes Toth, M.D., Ph.D.
Eric Hoopfer, Ph.D.
Hyosang Lee, Ph.D.
Isabelle S. Peter Lashgari Faghani, Ph.D.

Senior Research Associates

Mary An-yuan Yui, Ph.D.

Senior Faculty Associate

Alice S. Huang, Ph.D.

Visiting Associates

Clare Baker, Ph.D.
Elaine L. Bearer, Ph.D., M.D.
Peter Clote, Ph.D.
Scott Fraser, Ph.D.
Jordi Garcia-Ojalvo, Ph.D.
Taekjp Ha, Ph.D.
Elaine Hsiao, Ph.D.
Yongning He, Ph.D.
Hyoung Ihl Kim, Ph.D.
Brian Lee, M.D., Ph.D.
Carmel Levitan, Ph.D.
Charles Liu, M.D., Ph.D.
Stefano Lonardi, Ph.D.
Sylvia Lopez-Vetrone, Ph.D.
Hongyu Ma, Ph.D.
Eric Mjolsness, Ph.D.
Alan Moses, Ph.D.
Michael C. Mossing, Ph.D.
Sua Myong, Ph.D.
Alexandre Okano, Ph.D.
Carmie Puckett Robinson, M.D.
Yannick Rondelez, Ph.D.
Ian Ross, M.D.
Ueli Rutishauser, Ph.D.
Tarciso Velho, Ph.D

Member of the Beckman Institute

Sonja Hess, Ph.D.
Russell E. Jacobs, Ph.D.

Members of the Professional Staff

Igor Antoshechkin, Ph.D.
Janet F. Baer, D.V.
L. Elizabeth Bertani, Ph.D.
Bruce Cohen, Ph.D.
Andres Collazo, Ph.D.
Benjamin E. Deverman, Ph.D.
Rochelle A. Diamond, B.A.
Ali Khoshnan, Ph.D.
Evgueniy V. Lubenov, Ph.D.
Hans-Michael Muller, Ph.D.
Alex Nisthal, Ph.D.
Ker-hwa Ou, M.S.
Shirley Pease, B.Sc.
Andrew J. Ransick, Ph.D.
Bruce Shapiro, Ph.D.
Jost Vielmetter, Ph.D.
Anthony P. West, Jr., Ph.D.
Xiaowei Zhang, Ph.D.
Jie Zhou, Ph.D.

Senior Postdoctoral Scholars

Michael Bethune, Ph.D.
Ashwin Gopinath, Ph.D.
Satoshi Hirose, Ph.D.
Hiroyuki Hosokawa, PhD.
Nikolai Kandul, Ph.D.
Hao Yuan Kueh, Ph.D.
Paul Thomas Tarr, Ph.D.
Grigory Tikhomirov, Ph.D.

Postdoctoral Scholars

Tyson Aflalo, Ph.D.
Omar Akbari, Ph.D.
Yaron Antebi, Ph.D.
Salome Antolin y Moura de Oliveira e Silva, Ph.D.
Hiroki Asari, Ph.D.
Sreeram Balasubramanian, Ph.D.
Namrata Bali, Ph.D.
Pinglei Bao, Ph.D.
Anna Basalova Buchman, Ph.D.
Brittany Belin, Ph.D.[1]
Megan Bergkessel, Ph.D.[1]
Lacramioara Bintu, Ph.D.
Mario Blanco, Ph.D.
Mark Budde, Ph.D.
Emily Capra, Ph.D.
Robert Carrillo, Ph.D.
Stephen Carter, Ph.D.
Collin Challis, Ph.D.
Le Chang, Ph.D.
Audrey Chen, Ph.D.
Shun Jia Chen, Ph.D.
Yung-Chia Chen, Ph.D.
Andrea Choe, M.D., Ph.D.
Vasileios Christopoulos, Ph.D.
Hiutung Chu, Ph.D.

Kyle Costa, Ph.D.
Emmanuel De Los Santos, Ph.D.
William DePas, Ph.D.
Fangyuan Ding, Ph.D.
Brian J. Duistermars, Ph.D.
Pauline Durand, Ph.D.[1]
Roberto Feuda, Ph.D.
Kirsten Frieda, Ph.D.
Xiaojing Gao, Ph.D.
Debnath Ghosal, Ph.D.
Srimoyee Ghosh, Ph.D.
William Tyler Gibson, Ph.D.
Ysabel Giraldo, Ph.D.
Stephen A. Green, Ph.D.
Alon Grinbaum, Ph.D.
Harry Gristick, Ph.D.
Jyothi Swaroop Guntupalli, Ph.D.
Cai Guo, Ph.D.
Brandon Henderson, Ph.D.
Beverley M. Henley, Ph.D.
Lisa Marie Hochrein, Ph.D.
Weizhe Hong, Ph.D.
Uladzislau Hryshkevich, Ph.D.
Yen-Ping Hsueh, Ph.D.
Junho Hur, Ph.D.
Erica Hutchins, Ph.D.
Andrew Jewett, Ph.D.
Shuai Jiang, Ph.D.
Alok Joglekar, Ph.D.
Tomomi Karigo, Ph.D.
Spencer Kellis, Ph.D.
Ann Kennedy, Ph.D.
Laura Kerosuo-Pahlberg, Ph.D.
Collin Kieffer, Ph.D.
Daniel Kim, Ph.D.
Ji Eun Kim, Ph.D.
Christian Klaes, Ph.D.
Sebastian Kopf, Ph.D.
Theodora Koromila, Ph.D.
Brenna Krieger, Ph.D.
Ezgi Kunttas-Tatli, Ph.D.
Adrian Le Thomas, Ph.D.
Daniel Allen Lee, Ph.D.
Guideng Li, Ph.D.
Jing Li, Ph.D.
Juan Li, Ph.D.
Pulin Li, Ph.D.
Ting Li, Ph.D.
Wei Li, Ph.D.
Yatang Li, Ph.D.
Yihan Lin, Ph.D.
Theodore Lindsay, Ph.D.
Xing Liu, Ph.D.
Frank Macabenta, Ph.D.
Shrawan Mageswaran, Ph.D.
Devdoot Majumdar, Ph.D.
Siarhei Manakou, Ph.D.
Mati Mann, Ph.D.
Joseph Markson, Ph.D.
Colleen McHugh, Ph.D.
Prashant Mishra, Ph.D.
Felipe Monteleone Vieceli, Ph.D.
Eric A. Mosser, Ph.D.
Christina Murko, Ph.D.
Blaise Ndjamen, Ph.D.
Brittany D. Needham, Ph.D.
Simon Neubauer, Ph.D.1
Lam Nguyen, DVM, Ph.D.
Thang Van Nguyen, Ph.D.
Maria Ninova, Ph.D.
Jang-Huyn Oh, Ph.D.
Grigorios Oikonomou, Ph.D.
Noah Ollikainen, Ph.D.
Davi Ortega Ribeiro, Ph.D.
Chen-Yin Ou, Ph.D.
Maria Papadopoulou, Ph.D.
Suparna Patowary, Ph.D.
Nathanael Prunet, Ph.D.
Lisa Racki, Ph.D.
Pavan Ramdya, Ph.D.
Justin Reitsma, Ph.D.
Ryan Remedios, Ph.D.
Daniela Roellig, Ph.D.
Crystal Rogers, Ph.D.
Ivo Ros, Ph.D.
Arun Sampathkumar, Ph.D.
Timothy Sampson, Ph.D.
Luis Oscar Sanchez Guardado, Ph.D.
Tomokazu Sato, Ph.D.
Louise Scharf, Ph.D.
Hillel Schwartz, Ph.D.[1]
Gil Sharon, Ph.D.
Nicholas Shikuma, Ph.D.
Chun-Shik Shin, Ph.D.
Ryoji Shinya, Ph.D.
Amol Shivange, Ph.D.
Daniel Siegal-Gaskins, Ph.D.
Marcos Simoes Costa, Ph.D.
Zakary Singer, Ph.D.
Chanpreet Singh, Ph.D.
Beth Stadtmueller, Ph.D.
Vincent Andrew Stepanik, Ph.D.
Noelle Stiles, Ph.D.
Poorna Subramanian, Ph.D.[1]
Jingjing Sun, Ph.D.
Min-Kyung Sung, Ph.D.
Matthew Swulius, Ph.D.[1]
Jennifer Treweek, Ph.D.
Nathanie Trisnadi, Ph.D.
Vikas Trivedi, Ph.D.
Rosa Anna Uribe, Ph.D.
Anand Teertha Vaidya, Ph.D.
Floris Van Breugel, Ph.D.
Ward Walkup, Ph.D.
Teagan Wall, Ph.D.
Han Wang, Ph.D.

Timothy M. Wannier, Ph.D.
Alexandre Webster, Ph.D.
Peter Weir, Ph.D.
Wei-Li Wu, Ph.D.
Tanya R. Yakushi, Ph.D.
An Yan, Ph.D.
Qing Yao, Ph.D.
Hanako, Yashiro, Ph.D.
Melis Yilmaz Balban, Ph.D.
John Yong, Ph.D.
Moriel Zelikowsky, Ph.D.
Yun Zhou, Ph.D.

[1] *Joint appointment with Howard Hughes Medical Institute*

Visitors
Constantine Evans, Ph.D.
Jan Kaminski, Ph.D.
Rajan Kulkarni, Ph.D.
Jasna Markovac, Ph.D.
Kenji Oki, Ph.M.
Marketa Pernisova, Ph.D.
Tsu-Te (Judith) Su, Ph.D.
Jonas Ungerback, Ph.D.
Yanling Wang, Ph.D.
Kyongsik Yun, Ph.D.
Marketa Zadarska, Ph.D.

Division of Chemistry and Chemical Engineering

Jacqueline K. Barton, *Chair*
John F. Brady, *Executive Officer for Chemical Engineering*
Sarah Reisman, *Executive Officer for Chemistry*
Shu-ou Shan, *Executive Officer for Biochemistry and Molecular Biophysics*

Professors Emeriti

Fred C. Anson, Ph.D., D.h.c.
Elizabeth W. Gilloon Professor of Chemistry
John D. Baldeschwieler, Ph.D.
J. Stanley Johnson Professor and Professor of Chemistry
John E. Bercaw, Ph.D.
Centennial Professor of Chemistry
Sunney I. Chan, Ph.D.
George Grant Hoag Professor of Biophysical Chemistry
George R. Gavalas, Ph.D.
Chemical Engineering
John D. Roberts, Ph.D., Dr.rer. Nat.h.c., Sc.D.h.c., D.Sc.h.c.
Institute Professor of Chemistry

Senior Research Associates Emeriti

Richard E. Marsh, Ph.D.
Chemistry
William P. Schaefer, Ph.D.
Chemistry

Professors

Theodor Agapie, Ph.D.
Chemistry
Frances H. Arnold, Ph.D.
Dick and Barbara Dickinson Professor of Chemical Engineering, Bioengineering, and Biochemistry
Jacqueline K. Barton, Ph.D., D.Sc.h.c., D.L.h.c.
Arthur and Marian Hanisch Memorial Professor of Chemistry; Chair, Division of Chemistry and Chemical Engineering
Jesse L. Beauchamp, Ph.D.
Mary and Charles Ferkel Professor of Chemistry
Geoffrey A. Blake, Ph.D.
Cosmochemistry and Planetary Sciences and Chemistry
John F. Brady, Ph.D.
Chevron Professor of Chemical Engineering and Mechanical Engineering
Judith L. Campbell, Ph.D.
Chemistry and Biology
William C. Clemons, Ph.D.
Biochemistry
Mark E. Davis, Ph.D.
Warren and Katharine Schlinger Professor of Chemical Engineering
Peter B. Dervan, Ph.D., D.Sc.h.c.
Bren Professor of Chemistry
Dennis A. Dougherty, Ph.D.
George Grant Hoag Professor of Chemistry
Richard C. Flagan, Ph.D.
Irma and Ross McCollum-William H. Corcoran Professor of Chemical Engineering and Environmental Science and Engineering
Gregory C. Fu, Ph.D.
Altair Professor of Chemistry
Konstantinos P. Giapis, Ph.D.
Chemical Engineering
William A. Goddard III, Ph.D.
Charles and Mary Ferkel Professor of Chemistry, Materials Science, and Applied Physics
Harry B. Gray, Ph.D., D.Sc.h.c., Laurea h.c., Fil.Dr.h.c., D.L.h.c.
Arnold O. Beckman Professor of Chemistry and Founding Director of the Beckman Institute
Robert H. Grubbs, Ph.D., Nobel Laureate
Victor and Elizabeth Atkins Professor of Chemistry
James R. Heath, Ph.D.
Elizabeth W. Gilloon Professor and Professor of Chemistry
Linda C. Hsieh-Wilson, Ph.D.
Chemistry
Rustem F. Ismagilov, Ph.D.
Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering
Nathan S. Lewis, Ph.D.
George L. Argyros Professor and Professor of Chemistry

Rudolph A. Marcus, Ph.D., D.Sc.h.c., Fil.Dr.h.c., D.h.c., Nobel Laureate
John G. Kirkwood and Arthur A. Noyes Professor of Chemistry
Stephen L. Mayo, Ph.D.
Bren Professor of Biology and Chemistry
B. Vincent McKoy, Ph.D.
Theoretical Chemistry
Thomas F. Miller III, Ph.D.
Chemistry
Mitchio Okumura, Ph.D.
Chemical Physics
Carl S. Parker, Ph.D.
Biochemistry
Jonas C. Peters, Ph.D.
Bren Professor of Chemistry
Douglas C. Rees, Ph.D.[1]
Roscoe Gilkey Dickinson Professor of Chemistry
Sarah E. Reisman, Ph.D.
Chemistry
John H. Seinfeld, Ph.D., D.Sc.h.c.
Louis E. Nohl Professor and Professor of Chemical Engineering
Shu-ou Shan, Ph.D.
Chemistry
Brian M. Stoltz, Ph.D.
Professor of Chemistry
David A. Tirrell, Ph.D., D.h.c.
Ross McCollum–William H. Corcoran Professor and Professor of Chemistry and Chemical Engineering
Zhen-Gang Wang, Ph.D.
Lawrence A. Hanson Jr. Professor of Chemical Engineering
Daniel P. Weitekamp, Ph.D.
Chemical Physics
Ahmed H. Zewail, Ph.D., D.Sc.h.c., D.h.c., D.Univ.h.c., D.Phil.h.c., LL.D.h.c., M.D.h.c., Nobel Laureate
Linus Pauling Professor of Chemistry and Professor of Physics

[1] *Joint appointment with Howard Hughes Medical Institute*

Assistant Professors

Long Cai, Ph.D.
Chemistry
Andre Hoelz, Ph.D.
Chemistry
Mikhail G. Shapiro, Ph.D.
Chemical Engineering

Lecturers

Kathryn Bikle, M.A.
Chemistry
Nathan Dalleska, Ph.D.
Chemistry
Sonjong Hwang, Ph.D.
Chemical Engineering
Jeffrey Mendez, Ph.D.
Chemistry
Mona Shahgholi, Ph.D.
Chemistry
Scott Virgil, Ph.D.
Chemistry
Michael Vicic, Ph.D.
Chemical Engineering
Jay Winkler, Ph.D.
Chemistry

Faculty Associates

Jay A. Labinger, Ph.D.
Chemistry
Jay R. Winkler, Ph.D.
Chemistry

Visiting Associates

Ian Booth, Ph.D.
Biochemistry
Ara Chutjian, Ph.D.
Chemistry
Stephen J. Forman, M.D.
Chemical Engineering
James B. Howard, Ph.D.
Chemistry
Jian Jin, Ph.D.
Atomic Physics
Yusuke Kita
Organic Chemistry
Clifford Kubiak, Ph.D.
Chemistry
Roy A. Periana, Ph.D.
Chemistry
Adrian Ponce, Ph.D.
Chemistry
Manuel Soriaga, Ph.D.
Chemistry
Eric D. A. Stemp, Ph.D.
Chemistry
Robert D. Tanner, Ph.D.
Chemical Engineering
Yun Yen, M.D., Ph.D.
Pathology and Cell Biology

Members of the Beckman Institute

Bruce S. Brunschwig, Ph.D.
Jay R. Winkler, Ph.D.

Members of the Professional Staff

Suresha Guptha, M.S.
Chemical Engineering
John Gregoire, Ph.D.
Chemistry
Joint Center for Artificial Photosynthesis
Lawrence R. Henling, M.S.
Chemistry
Sonjong Hwang, Ph.D.
Chemistry
Hans (Joachim) Lewerenz, Ph.D.
Chemistry
Joint Center for Artificial Photosynthesis
Boris Merinov, Ph.D.
Chemistry
Slobodan Mitrovic, Ph.D.
Chemistry
Joint Center for Artificial Photosynthesis
Mona Shahgholi, Ph.D.
Chemistry
David Vander Velde, Ph.D
Chemistry

Senior Postdoctoral Scholar

James Blakemore, Ph.D.
Shu Hu, Ph.D.
Choon Woo Lee, Ph.D.
Melanie P. Yen, Ph.D.

Postdoctoral Scholars

Damien Amedro, Ph.D.
Dinesh Aluthge, Ph.D.
Christopher Bates, Ph.D.
Chandrabali Bhattacharya, Ph.D.
Siti Nurhanna Binte Riduan, Ph.D.
Chris Bley, Ph.D.
Raymond Bourdeau, Ph.D.
Oliver F. Brandenberg, Ph.D.
Bradley Brennan, Ph.D.
Aimee Bryan, Ph.D.
Andrew Buller, Ph.D.
David Bunck, Ph.D.
Miguel Caban-Acevedo, Ph.D.
Marchello Cavitt, Ph.D.
Shawn Chatman, Ph.D.
Bin Chen, Ph.D.
Tao Cheng, Ph.D.
Hyun Ju Cho, Ph.D.
Gyeong Shin Choi, Ph.D.
Joonhyuk Choi, Ph.D.
Priya Choudhry, Ph.D.
Cooper Citek, Ph.D.
Ahmet Faruk Coskun, Ph.D.
Robert Craig, Ph.D.
Kyle Cummins, Ph.D.
Mostafa Jon Dadras, Ph.D.
Mita Dasog, Ph.D.
Sujit Datta, Ph.D.
Graham de Ruiter, Ph.D.
Feizhi Ding, Ph.D.
Sheel Dodani, Ph.D.
Peter Dornan, Ph.D.
Michiel Dusselier, Ph.D.
Noah Fine Nathel, Ph.D.
Paul Finn, Ph.D.
Sonja Angelique Francis, Ph.D.
Xuewen Fu, Ph.D.
Ariel Furst, Ph.D.
Betar Gallant, Ph.D.
Alice Ghidini, Ph.D.
Wesley Glenn, Ph.D.
Pablo Guzman, Ph.D.
Michael Haibach, Ph.D.
Graham Daniel Hamblin, Ph.D.
Stephen Hammer, Ph.D.
Si-Ping Han, Ph.D.
Zhiji Han, Ph.D.
Mohammed Hassan Mohammed, Ph.D.
Masaki Hayashi, Ph.D.
Ting-Fang He, Ph.D.
Marco Heinen, Ph.D.
Shabnam Hematian, Ph.D.
Myles Herbert, Ph.D.
Lukas Walter Herwig, Ph.D.
Matthew James Hesse, Ph.D.
John Hethcox, Ph.D.
Natasha Hodas, Ph.D.
Jianbo Hu, Ph.D.
Pengfei Huo, Ph.D.
Kazato Inanaga, Ph.D.
Alnald Javier, Ph.D.
Courtney Jenkins, Ph.D.
Tiezheng Jia, Ph.D.
Jian Jiang, Ph.D.
Jimmy John, Ph.D.
Miles Johnson, Ph.D.
Sek-Bik Jennifer Kan, Ph.D.
Pavan Kancharla, Ph.D.

Eugenia Khorosheva, Ph.D.
Madeleine Kieffer, Ph.D.
Max Klatte, Ph.D.
Alexis Komor, Ph.D.
Wesley Kramer, Ph.D.
Jerome Lacroix, Ph.D.
Yan Choi Lam, Ph.D.
Choon Woo Lee, Ph.D.
Juneyoung Lee, Ph.D.
Matthew C. Lehman, Ph.D.
Johannes Leppa, Ph.D.
Dana Levine, Ph.D.
Heng Li, Ph.D.
Fu-Cheng Liang, Ph.D.
Allegra Liberman-Martin, Ph.D.
Alejo M. Lifschitz Arribio, Ph.D.
Antti Lignell, Ph.D.
Hanna Lignell, Ph.D.
Ku-Feng Lin, Ph.D.
Tzu-Pin Lin, Ph.D.
Haihua Liu, Ph.D.
Wenbo Liu, Ph.D.
Yuanyue Liu, Ph.D.
Justin Lomont, Ph.D.
Jiaozhi Lu, Ph.D.
Liang Ma, Ph.D.
Robert MacFarlane, Ph.D.
Yusuke Makida, Ph.D.
Lionel Marcelis, Ph.D.
George Mobbs, Ph.D.
Octavio Mondragon Palomino, Ph.D.
Timothy Patrick Montgomery, Ph.D.
Jared Thomas Moore, Ph.D.
Xin Mu, Ph.D.
Arnab Mukherjee, Ph.D.
Javier Murciano Calles, Ph.D.
Arundha Nag, Ph.D.
Ebrahim Najafi, Ph.D.
Adela Nano, Ph.D.
Saber Naserifar, Ph.D.
Songming Peng, Ph.D.
Thibaud Perriches, Ph.D.
Christopher Prier, Ph.D.
Norbert Radacsi, Ph.D.
Hans Renata, Ph.D.
Austin Rice, Ph.D.
Jesus Rodriguez-Manzano, Ph.D.
David Kingsland Romney, Ph.D.
Daisuke Saito, Ph.D.
Brian Sanders, Ph.D.
Brett Savoie, Ph.D.
Kathryn Nicole Schaefer, Ph.D.
Jens Schmidt, Ph.D.
Michael Schulz, Ph.D.
Gregg Schwarzwalder, Ph.D.
Bo Shen, Ph.D.
Daniel Sieh, Ph.D.
Amanda Silberstein, Ph.D.
Thomas Spatzal, Ph.D.
David Steelman, Ph.D.
Tobias T. Stuwe, Ph.D
Zixue Su, Ph.D.
Xing Wen Sun, Ph.D.
Jerzy Olgierd Szablowski, Ph.D.
Karsten Thierbach, Ph.D.
Aiko Umeda, Ph.D.
Gael Ung, Ph.D.
Giovanni Vanacore, Ph.D.
Reid Van Lehn, Ph.D.
Mark Bernardus van Eldijk, Ph.D.
Jesus Velasquez, Ph.D.
Ana Raquel Viegas Correia, Ph.D.
Sandor Volkan-Kacso, Ph.D.
Andrew Chih-Kae Wang, Ph.D.
Jun Wang, Ph.D.
Alyson Weidmann, Ph.D.
Ralph Welsch, Ph.D.
Joshua S. Wiley, Ph.D.
Daan Witters, Ph.D.
William Wolf, Ph.D.
Xiangyou Xing, Ph.D.
Hai Xiao, Ph.D.
Alexander Xu, Ph.D.
Chen Xu, Ph.D.
Min Xue, Ph.D.
Umi Yamamoto, Ph.D.
Delian Yang, Ph.D.
Fan Yang, Ph.D.
Janet Gloria Yang, Ph.D.
Yunxi Yao, Ph.D.
Byung-Kuk Yoo, Ph.D.
Yasushi Yoshida, Ph.D.
Jing Yu, Ph.D.
Pengfei Zhang, Ph.D.
Jing Zhou, Ph.D.
Ran Zhao, Ph.D.
Daniel Todd Ziegler, Ph.D.

Visitors

Ladan Foose, Ph.D.
Chemical Engineering
Rohan A. Hule, Ph.D.
Materials Science and Engineering
Zuleikha Kurji, Ph.D.
Chemistry
Alyssia Lilio, M.S.
Chemistry
Daniel Mattle, M.S.
Structural Biology
Matthew S. Mattson, Ph.D.
Applied Physics
Xiangying Meng, Ph.D.
Physics

Steven Millward, Ph.D.
Biochemistry
Nicholas G. Nickols, M.D. Ph.D.
Chemistry
Kathryn Perrine
Chemistry
Young Shik Shin, Ph.D.
Bioengineering
Andrew Udit, Ph.D.
Chemistry
Ted Yu, Ph.D.
Materials Science
Liang (Jack) Zhang, M.S.
Chemical Engineering
Wenbin Zhang, Ph.D.
Polymer Science

Division of Engineering and Applied Science

Guruswami Ravichandran
Otis Booth Leadership Chair
Peter Schröder,
EAS Division Deputy Chair
Kaushik Bhattacharya
Executive Officer for Mechanical and Civil Engineering
Mathieu Desbrun
Executive Officer for Computing and Mathematical Sciences
Ali Hajimiri
Executive Officer for Electrical Engineering
Yu-Chong Tai
Executive Officer for Medical Engineering
Kerry J. Vahala
Executive Officer for Applied Physics and Materials Science
Paul O. Wennberg
Executive Officer fo Environmental Science and Engineering

Professors Emeriti

Allan J. Acosta, Ph.D.
Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering
Christopher E. Brennen, D.Phil.
Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering
William B. Bridges, Ph.D.
Carl F Braun Professor of Engineering
Norman H. Brooks, Ph.D.
James Irvine Professor of Environmental and Civil Engineering
K. Mani Chandy, Ph.D.
Simon Ramo Professor of Computer Science
Donald S. Cohen, Ph.D.
Charles Lee Powell Professor of Applied Mathematics
Noel R. Corngold, Ph.D.
Applied Physics
Fred E. C. Culick, Ph.D.
Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion
Thomas E. Everhart, Ph.D., D.L.h.c., D.h.c.
Electrical Engineering and Applied Physics
Joel N. Franklin, Ph.D.
Applied Mathematics
David L. Goodstein, Ph.D.
Frank J. Gilloon Distinguished Teaching and Service Professor and Professor of Physics and Applied Physics
Roy W. Gould, Ph.D.
Simon Ramo Professor of Engineering
Hans G. Hornung, Ph.D.
C. L. "Kelly" Johnson Professor of Aeronautics
Wilfred D. Iwan, Ph.D.
Applied Mechanics
Paul C. Jennings, Ph.D.
Civil Engineering and Applied Mechanics
Wolfgang G. Knauss, Ph.D.
Theodore von Kármán Professor of Aeronautics and Applied Mechanics
Anthony Leonard, Ph.D.
Theodore von Kármán Professor of Aeronautics
E. John List, Ph.D.
Environmental Engineering Science
Robert J. McEliece, Ph.D.
Allen E. Puckett Professor and Professor of Electrical Engineering
Carver A. Mead, Ph.D., D.Sc.h.c., D.h.c.
Gordon and Betty Moore Professor of Engineering and Applied Science
James J. Morgan, Ph.D., D.Sc.h.c.
Marvin L. Goldberger Professor of Environmental Engineering Science
Marc-Aurele Nicolet, Ph.D.
Electrical Engineering and Applied Physics
Anatol Roshko, Ph.D.
Theodore von Kármán Professor of Aeronautics
Rolf H. Sabersky, Ph.D.
Mechanical Engineering
Theodore Y. Wu, Ph.D.
Engineering Science

Professors

Yaser S. Abu-Mostafa, Ph.D.
Electrical Engineering and Computer Science
Jess F. Adkins, Ph.D.
Geochemistry and Global Environmental Science
José E. Andrade, Ph.D.
Civil and Mechanical Engineering
Domniki Asimaki, Sc.D.
Mechanical and Civil Engineering
Harry A. Atwater, Jr., Ph.D.
Howard Hughes Professor of Applied Physics and Materials Science
Joanna M. Austin, Ph.D.
Aerospace
Alan H. Barr, Ph.D.
Computer Science
James L. Beck, Ph.D.
George H. Housner Professor of Engineering and Applied Science
Paul M. Bellan, Ph.D.
Applied Physics
Kaushik Bhattacharya, Ph.D.
Howell N. Tyson, Sr., Professor of Mechanics and Professor of Materials Science
Guillaume Blanquart, Ph.D.
Mechanical Engineering
John F. Brady, Ph.D.
Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering
Jehoshua Bruck, Ph.D.
Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering
Oscar P. Bruno, Ph.D.
Applied and Computational Mathematics
Joel W. Burdick, Ph.D.
Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering
Timothy E. Colonius, Ph.D.
Mechanical Engineering
John O. Dabiri, Ph.D.
Aeronautics and Bioengineering
Chiara Daraio, Ph.D.
Aeronautics and Applied Physics
Mathieu Desbrun, Ph.D.
John W. and Herberta M. Miles Professor of Computing and Mathematical Sciences
Paul E. Dimotakis, Ph.D.
John K. Northrop Professor of Aeronautics and Professor of Applied Physics
John C. Doyle, Ph.D.
Jean-Lou Chameau Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering
Michelle Effros, Ph.D.
George Van Osdol Professor of Electrical Engineering
James P. Eisenstein, Ph.D.
Frank J. Roshek Professor of Physics and Applied Physics
Charles Elachi, Ph.D.
Electrical Engineering and Planetary Science
Michael Elowitz, Ph.D.1
Biology and Bioengineering
Azita Emami, Ph.D.
Electrical Engineering
Katherine T. Faber, Ph.D.
Simon Ramo Professor of Materials Science
Richard C. Flagan, Ph.D.
Irma and Ross McCollum–William H. Corcoran Professor of Chemical Engineering and Professor of Environmental Science and Engineering
Brent T. Fultz, Ph.D.
Barbara and Stanley R. Rawn, Jr., Professor of Materials Science and Applied Physics
Morteza Gharib, Ph.D.
Hans W. Liepmann Professor of Aeronautics and Professor of Bioinspired Engineering
William A. Goddard III, Ph.D.
Charles and Mary Ferkel Professor of Chemistry, Materials Science, and Applied Physics
Julia R. Greer, Ph.D.
Materials Science and Mechanics
Sossina M. Haile, Ph.D.
Carl F Braun Professor of Materials Science and Chemical Engineering
Ali Hajimiri, Ph.D.
Thomas G. Myers Professor of Electrical Engineering
John F. Hall, Ph.D.
Civil Engineering
Babak Hassibi, Ph.D.
Gordon M. Binder/Amgen Professor of Electrical Engineering

Thomas H. Heaton, Ph.D.
Engineering Seismology
Michael R. Hoffmann, Ph.D.
James Irvine Professor of Environmental Science
Yizhao Thomas Hou, Ph.D.
Charles Lee Powell Professor of Applied and Computational Mathematics
Melany L. Hunt, Ph.D.
Dotty and Dick Hayman Professor of Mechanical Engineering
William L. Johnson, Ph.D.
Ruben F. and Donna Mettler Professor of Engineering and Applied Science
Nadia Lapusta, Ph.D.
Mechanical Engineering and Geophysics
Jared R. Leadbetter, Ph.D.
Environmental Microbiology
Steven Low, Ph.D.
Computer Science and Electrical Engineering
Alain J. Martin, Ing.
Computer Science
Beverley J. McKeon, Ph.D.
Aeronautics
Daniel I. Meiron, Sc.D.
Fletcher Jones Professor of Aeronautics and Applied and Computational Mathematics
Richard M. Murray, Ph.D.
Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering
Michael Ortiz, Ph.D.
Frank and Ora Lee Marble Professor of Aeronautics and Mechanical Engineering
Houman Owhadi, Ph.D.
Applied and Computational Mathematics and Control and Dynamical Systems
Oskar J. Painter, Ph.D.
John G Braun Professor of Applied Physics
Sergio Pellegrino, Ph.D.
Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering, and JPL Senior Research Scientist
Pietro Perona, D.Eng., Ph.D.
Allen E. Puckett Professor of Electrical Engineering
Robert Phillips, Ph.D.
Fred and Nancy Morris Professor of Biophysics and Biology
Niles A. Pierce, D.Phil.
Applied and Computational Mathematics and Bioengineering
Dale I. Pullin, Ph.D.
Theodore von Kármán Professor of Aeronautics
Guruswami Ravichandran, Ph.D., D.h.c.
Professor of Aerospace and Mechanical Engineering; Otis Booth Leadership Chair
Ares J. Rosakis, Ph.D.
Theodore von Kármán Professor of Aeronautics and Mechanical Engineering
Michael L. Roukes, Ph.D.
Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering
David B. Rutledge, Ph.D.
Kiyo and Eiko Tomiyasu Professor of Engineering
Axel Scherer, Ph.D.
Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics
Tapio Schneider, Ph.D.
Frank J. Gilloon Professor of Environmental Science and Engineering
Peter Schröder, Ph.D.
Shaler Arthur Hanisch Professor of Computer Science and Applied and Computational Mathematics
Leonard J. Schulman, Ph.D.
Computer Science
Keith C. Schwab, Ph.D.
Applied Physics
John H. Seinfeld, Ph.D., D.Sc.h.c.
Louis E. Nohl Professor and Professor of Chemical Engineering
Joseph E. Shepherd, Ph.D.
C. L. "Kelly" Johnson Professor of Aeronautics and Professor of Mechanical Engineering
Athanassios G. Siapas, Ph.D.
Computation and Neural Systems
Yu-Chong Tai, Ph.D.
Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering
Sandra M. Troian, Ph.D.
Applied Physics, Aeronautics, and Mechanical Engineering
Joel A. Tropp, Ph.D.
Applied and Computational Mathematics

Christopher Umans, Ph.D.
Computer Science
Kerry J. Vahala, Ph.D.
Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics
P. P. Vaidyanathan, Ph.D.
Electrical Engineering
Paul O. Wennberg, Ph.D.
R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering
Adam C. Wierman, Ph.D.
Computer Science
Erik Winfree, Ph.D.
Computer Science, Computation and Neural Systems, and Bioengineering
Changhuei Yang, Ph.D.
Electrical Engineering, Bioengineering and Medical Engineering
Amnon Yariv, Ph.D.
Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering

Assistant Professors

Marco Bernardi, Ph.D.
Applied Physics and Materials Science
Simona Bordoni, Ph.D.
Environmental Science and Engineering
Venkat Chandrasekaran, Ph.D.
Computing and Mathematical Sciences and Electrical Engineering
Hyuck Choo, Ph.D.
Electrical Engineering
Andrei Faraon, Ph.D.
Applied Physics and Materials Science
Dennis M. Kochmann, Dr. -Ing.
Aerospace
Victoria Kostina, Ph.D.
Electrical Engineering
Katrina A. C. Ligett, Ph.D.
Computer Science and Economics
Austin J. Minnich, Ph.D
Mechanical Engineering and Applied Physics
Stevan Nadj-Perge, Ph.D.
Applied Physics and Materials Science
Thomas Vidick, Ph.D.
Computing and Mathematical Sciences
Yisong Yue, Ph.D.
Computing and Mathematical Sciences

[1] *Joint with the Howard Hughes Medical Institute*

Instructors

Qin Li, Ph.D.
Theodore von Kármán Instructor in Computing and Mathematical Sciences

Lecturers

Dimitrios Antsos, Ph.D.
Electrical Engineering
John Baker, B.S.
Aerospace
Joseph G. Billock, Ph.D.
Computing and Mathematical Sciences
Roland Brockers, Ph.D.*
Mechanical and Civil Engineering
Robert Chess, M.B.A.
Engineering
Melissa S. Dabiri, Ph.D.
Engineering
Gregory L. Davis, Ph.D.
Aerospace
James Farrell, M.S.
Computing and Mathematical Sciences
Antony R. H. Fender, B.S.
Engineering
Trevor Foucher, B.S.
Computing and Mathematical Sciences
Anthony Freeman, Ph.D.
Aerospace
Thomas Fuchs, Ph.D.*
Mechanical and Civil Engineering
Carol M. Garland, B.A.
Applied Physics and Materials Science
Glen A. George, M.S.
Electrical Engineering
Alireza Ghaffari, M.S.
Applied Physics and Materials Science
Douglas C. Hofmann, Ph.D.
Applied Physics and Materials Science
Gerard J. Holzmann, Ph.D.
Computing and Mathematical Sciences

Joshua M. Hyman, Ph.D.
Computing and Mathematical Sciences
Rahul Kumar, Ph.D.*
Computing and Mathematical Sciences
Eugene Lavretsky, Ph.D.
Computing and Mathematical Sciences
Santiago Lombeyda, M.S.
Engineering
Douglas G. MacMartin, Ph.D.
Computing and Mathematical Sciences
Larry H. Matthies, Ph.D.*
Mechanical and Civil Engineering
Barry B. Megdal, Ph.D.
Electrical Engineering
Michael Mello, Ph.D.
Mechanical and Civil Engineering
Niema M. Pahlevan, Ph.D.*
Medical Engineering
Danny Petrasek, Ph.D.
Medical Engineering
Donald Pinkston III, B.S.
Computing and Mathematical Sciences
James E. Polk, Ph.D.
Aerospace
Vasumathi Raman, Ph.D.*
Computing & Mathematical Sciences
Carol W. Readhead, Ph.D.
Engineering
Brandon Rothrock, Ph.D.*
Mechanical and Civil Engineering
Michael S. Ryoo, Ph.D.*
Mechanical and Civil Engineering
Daniel Scharf, Ph.D.
Aerospace
Douglas L. Smith, B.S.
Engineering
John P. Van Deusen, B.S.
Mechanical and Civil Engineering
Michael C. Vanier, Ph.D.
Computing and Mathematical Sciences
Jakob J. Van Zyl, Ph.D.
Electrical Engineering
Stephan Weiss, Ph.D.*
Mechanical and Civil Engineering
Ed Zschau, Ph.D.*
Engineering

** In residence 2014–15*

Research Professors

Marios D. Demetriou, Ph.D.
Applied Physics and Material Science
Douglas G. MacMartin, Ph.D.
Computing and Mathematical Sciences
Hillary Mushkin, MFA
Art and Design
Paul W. K. Rothemund, Ph.D.
Bioengineering, Computing & Mathematical Sciences, and Computation and Neural Systems

Research Assistant Professor

Monica D. Kohler, Ph.D.
Mechanical and Civil Engineering

Senior Research Fellows

Damien P. Woods, Ph.D.
Computing and Mathematical Sciences

Senior Faculty Associate

Gerard J. Holzmann, Ph.D.
Computing and Mathematical Sciences
Jakob J. Van Zyl, Ph.D.
Electrical Engineering and Aerospace
Sander Weinreb, Ph.D.
Electrical Engineering

Faculty Associates

Alexis C. Livanos, Ph.D.
Aerospace
G. Jeffrey Snyder, Ph.D.
Applied Physics and Materials Science

Moore Distinguished Scholar

James R. Rice, Ph.D.
Mechanical and Civil Engineering

Visiting Professors

Andrea P. Belz, Ph.D.*
Engineering

Daniel J. Bodony, Ph.D.*
Mechanical and Civil Engineering
Rodney J. Clifton, Ph.D.
Clark B. Millikan Visiting Professor of Aerospace
Bruno Crosignani, Lib.Doc.
Applied Physics and Materials Science
Emmanuel Gdoutos, Ph.D.
Clark B. Millikan Visiting Professor of Aerospace
Petros Koumoutsakos, Ph.D.
Clark B. Millikan Visiting Professor of Aerospace
Farshad Lahouti, Ph.D.*
Electrical Engineering
Kenneth A. Pickar, Ph.D.
Mechanical and Civil Engineering
Matei I. Radulescu, Ph.D.*
Mechanical and Civil Engineering

** In residence 2014–15*

Visiting Associates

Ebbe S. Andersen, Ph.D.
Computing and Mathematical Sciences
Lachlan L. H. Andrew, Ph.D.
Computing and Mathematical Sciences
Josette Bellan, Ph.D.
Mechanical and Civil Engineering
Applied Physics and Materials
Samuel Case Bradford V, Ph.D.
Aerospace
James B. Breckinridge, Ph.D.
Aerospace
Se-Myong Chang, Ph.D.
Aerospace
Lijun Chen, Ph.D.
Computing and Mathematical Sciences
Calum R. I. Chisholm, Ph.D.
Applied Physics and Materials Science
Young Dahl Cho, Ph.D.
Mechanical and Civil Engineering
Wongee Chun, Ph.D.
Environmental Science and Engineering
Agustin J. Colussi, Ph.D.
Environmental Science and Engineering
R. Dale Conner, Ph.D.
Applied Physics and Materials Science
Bruno Crosignani, Lib.Doc.
Applied Physics and Materials Science
Marie Csete, Ph.D.
Medical Engineering
Mamadou S. Diallo, Ph.D.
Environmental Science and Engineering
Elisa Franco, Ph.D.
Computing and Mathematical Sciences
James Goltz, Ph.D.
Mechanical and Civil Engineering
Seog-Tae Han, Ph.D.
Electrical Engineering
Seunghoon Han, Ph.D.
Applied Physics and Materials Science
Yong Hao, Ph.D.
Applied Physics and Materials Science
Douglas C. Hofmann, Ph.D.
Applied Physics and Materials Science
Philip Hon, Ph.D.
Applied Physics and Materials Science
Tzung K. Hsiai, Ph.D, M.D.
Medical Engineering
Jin Huang, Ph.D.
Computing and Mathematical Sciences
Mark S. Humayun, Ph.D.
Medical Engineering
Mikinori Ito, Ph.D.
Applied Physics and Materials Science
Sanggeun Jeon, Ph.D.
Electrical Engineering
Chenyang "Sunny" Jiang, Ph.D.
Environmental Science and Engineering
Sarah Keating, Ph.D.
Computing and Mathematical Sciences
Soonhyun Kim, Ph.D.
Environmental Science and Engineering
David Kremers, B.S.
Aerospace
Swaminathan Krishnan, Ph.D.
Mechanical and Civil Engineering
Deborah Kuchnir Fygenson, Ph.D.
Electrical Engineering

Farshad Lahouti, Ph.D.
Electrical Engineering
Hansuek Lee, Ph.D.
Applied Physics and Materials Science
Tai Kyu Lee, Ph.D.
Environmental Science and Engineering
Han Li, Ph.D.
Applied Physics and Materials Science
Jiangang Li, Ph.D.
Computing and Mathematical Sciences
Luiz M. Lourenco,Ph.D.
Aerospace
Xilin Lu, Ph.D.
Mechanical and Civil Engineering
Georgios Matheou, Ph.D.
Aerospace
Jong Hyun Na, Ph.D.
Applied Physics and Materials Science
Ralph Nuzzo, Ph.D.
Applied Physics and Materials Science
Hyunwoong Park, Ph.D.
Environmental Science and Engineering
Danny Petrasek, Ph.D.
Medical Engineering
George A. Rakuljic, Ph.D.
Applied Physics and Materials Science
Sylvie Ronel, Ph.D.
Aerospace
Phoebus Rosakis, Ph.D.
Aerospace
Brian D. Ross, Ph.D.
Medical Engineering
Charles G. Sammis, Ph.D.
Aerospace
Konrad H. Samwer, Ph.D.
Applied Physics and Materials Science
Andrew A. Shapiro-Scharlotta, Ph.D.
Aerospace
Peter H. Siegel, Ph.D.
Electrical Engineering
Hyun-Kon Song, Ph.D.
Applied Physics and Materials Science
Tabitha Swan-Wood, Ph.D.
Applied Physics and Materials Science
Luke Sweatlock, Ph.D.
Applied Physics and Materials Science
Eric Toberer, Ph.D.
Applied Physics and Materials Science
Tatiana G. Vinogradova
Aerospace
Daifa Wang, Ph.D.
Electrical Engineering
Wei Wang, Ph.D.
Electrical Engineering
Ming Xu, Ph.D.
Electrical Engineering
Yoshihiro Yamazaki, Ph.D.
Applied Physics and Materials Science
Jose Roberto Zenit Camacho, Ph.D.
Aerospace

Members of the Professional Staff

Nathan F. Dalleska, Ph.D.
Environmental Analysis Center
Guy A. DeRose, Ph.D.
Applied Physics and Materials Science
Carol M. Garland, B.A.
Kavli Nanoscience Institute
Alireza Ghaffari, M.S.
Applied Physics and Materials Science
Joel A. Haber, Ph.D.
Joint Center for Artificial Photosynthesis
Michael Hucka, Ph.D.
Computing and Mathematical Sciences
Suho Jung, Ph.D.
Joint Center for Artificial Photosynthesis
Chengxiang Xiang, Ph.D.
Joint Center for Artificial Photosynthesis

Senior Postdoctoral Scholars

Umut Aydemir, Ph.D.
Applied Physics and Materials Science
Remy Mevel, Ph.D.
Aerospace
Ruzan Sokhoyan, Ph.D.
Applied Physics and Materials Science
Zhiwen Zhang, Ph.D.
Computing and Mathematical Sciences

Postdoctoral Scholars

Muhammad Z. Alam, Ph.D.
KNI Postdoctoral Scholar in Applied Physics and Materials Science
Janina Bahnemann, Ph.D.
Environmental Science and Engineering
Siddharth Barman, Ph.D.
Center for the Mathematics of Information
Giulio Borghesi, Ph.D.
Mechanical and Civil Engineering
Stephen Bongiorno, Ph.D.
Aerospace
Federico Bosi, Ph.D.
Aerospace
Steven Branson, Ph.D.
Electrical Engineering
Victor Brar, Ph.D.
Applied Physics and Materials Science
Dennis Callahan, Jr., Ph.D.
Applied Physics and Materials Science
Kil-Byong Chai, Ph.D.
Applied Physics and Materials Science
Xiangwen Chen, Ph.D.
Mechanical and Civil Engineering
Wan Cheng, Ph.D.
Aerospace
Krishnamurthy Dvijotham, Ph.D.
Computing and Mathematical Sciences
Pilar Espinet Gonzalez, Ph.D.
Applied Physics and Materials Science
Azin Fahimi, Ph.D.
Medical Engineering
Kejie Fang, Ph.D.
Applied Physics and Materials Science
Samira Safaei Farahani, Ph.D.
Computing and Mathematical Sciences
Omar Fawzi, Ph.D.
Computing and Mathematical Sciences
Farzad Hassanzadeh, Ph.D.
Electrical Engineering
Stefanie Heyden, Ph.D.
Aerospace
Yutaka Hori, Ph.D.
Computing and Mathematical Sciences
Md. Zubaer Hossain, Ph.D.
Mechanical and Civil Engineering
Jing-Shun Huang, Ph.D.
Resnick Sustainability Institute Prize Postdoctoral Scholar in Applied Physics and Materials Science
Kathryn Jackson, Ph.D.
Aerospace
Justin T. Jasper, Ph.D.
Resnick Sustainability Institute Prize Postdoctoral Scholar in Environmental Science and Engineering
Stacey Jeffery, Ph.D.
IQIM Postdoctoral Scholar in Computing and Mathematical Sciences
Vanessa Jonsson, Ph.D.
Computing and Mathematical Sciences
Moureen Kemei, Ph.D.
Resnick Sustainability Institute Prize Postdoctoral Scholar in Applied Physics and Materials Science
Owen T. Kingstedt, Ph.D.
Aerospace
Sukmo Koo, Ph.D.
Medical Engineering
Panagiotis Kourdis, Ph.D.
Mechanical and Civil Engineering
Yu-Jung Lu, Ph.D.
Applied Physics and Materials Science
Jason Marshall, Ph.D.
Mechanical and Civil Engineering
Ho Wai (Howard) Lee, Ph.D.
Applied Physics and Materials Science
Jeong Lee, Ph.D.
Electrical Engineering
Nicolas Lee, Ph.D.
W. M. Keck Institute for Space Studies Postdoctoral Scholar in Aerospace
Kun Li, Ph.D.
Mechanical and Civil Engineering
Yue Li, Ph.D.
Electrical Engineering
Keng Wit Lim, Ph.D.
Mechanical and Civil Engineering
Yuan Luo, Ph.D.
Electrical Engineering
Elizabeth Luthman, Ph.D.
Aerospace

Laleh Majari Kasmaee, Ph.D.
Environmental Science and Engineering
Enrique Mallada Garcia, Ph.D.
Center for the Mathematics of Information
Catharine McGhan, Ph.D.
Computing and Mathematical Sciences
Josue Melguizo-Gavilanes, Ph.D.
Aerospace
Juan Pedro Mendez Granado, Ph.D.
Aerospace
Niema Mohammad Pahlevan, Ph.D.
James Boswell Postdoctoral Scholar in Medical Engineering
Sreekanth R. Nair, Ph.D.
Environmental Science and Engineering
Ragip Pala, Ph.D.
Applied Physics and Materials Science
Mauricio Ponga de la Torre, Ph.D.
Mechanical and Civil Engineering
Amuthan Ramabathiran, Ph.D.
Aerospace
Mahshid Roumi, Ph.D.
Environmental Science and Engineering
Haowen Ruan, Ph.D.
Electrical Engineering
Rebecca Saive, Ph.D.
Applied Physics and Materials Science
Oliver Schmidt, Ph.D.
Mechanical and Civil Engineering
Mahsa Shoaran, Ph.D.
Electrical Engineering
Eran Segev, Ph.D.
Applied Physics and Materials Science
Piyush Srivastava, Ph.D.
Computing and Mathematical Sciences
Tiago Stegun Vaquero, Ph.D.
Computing and Mathematical Sciences
Giulia Tagliabue, Ph.D.
Applied Physics and Materials Science
Christopher Thachuk, Ph.D.
Computing and Mathematical Sciences
Krishnan Thyagarajan, Ph.D.
Applied Physics and Materials Science
Madeleine Udell, Ph.D.
Computing and Mathematical Sciences
Emily Warmann, Ph.D.
Applied Physics and Materials Science
Wouter Mostert, Ph.D.
Aerospace
Xing Xie, Ph.D.
Environmental Science and Engineering
Daejong Yang, Ph.D.
Medical Engineering
Heng Yang, Ph.D.
Applied Physics and Materials Science
Yang Yang, Ph.D.
Environmental Science and Engineering
Hang Zhang, Ph.D.
Mechanical and Civil Engineering
Tian Zhong, Ph.D.
Applied Physics and Materials Science

Division of Geological and Planetary Sciences

John P. Grotzinger, *Chair*
Robert W. Clayton, *Divisional Academic Officer*
Michael C. Gurnis, *Director, Seismological Laboratory*
Paul O. Wennberg, *Director, Linde Center for Global Environmental Science*

Professors Emeriti

Arden L. Albee, Ph.D.
Geology and Planetary Science
Clarence R. Allen, Ph.D.
Geology and Geophysics
Donald S. Burnett, Ph.D.
Nuclear Geochemistry
Peter Goldreich, Ph.D.
Lee A. DuBridge Professor of Astrophysics and Planetary Physics
David G. Harkrider, Ph.D.
Geophysics
Hiroo Kanamori, Ph.D.
John E. and Hazel S. Smits Professor of Geophysics
Duane O. Muhleman, Ph.D.
Planetary Science
Jason B. Saleeby, Ph.D.
Geology
Leon T. Silver, Ph.D.
W. M. Keck Foundation Professor for Resource Geology
Hugh P. Taylor Jr., Ph.D.
Robert P. Sharp Professor of Geology
G. J. Wasserburg, Ph.D., D.h.c., D.Sc.h.c, Sc.D.h.c,
Crafoord Laureate, John D. MacArthur Professor of Geology and Geophysics
Peter J. Wyllie, Ph.D., D.Sc.h.c.
Geology

Professors

Jess F. Adkins, Ph.D.
Geochemistry and Global Environmental Science
Paul D. Asimow, Ph.D.
Geology and Geochemistry
Jean-Philippe Avouac, Doctorat
Geology
Geoffrey A. Blake, Ph.D.
Cosmochemistry and Planetary Sciences and Chemistry
Michael E. Brown, Ph.D.
Richard and Barbara Rosenberg Professor and Professor of Planetary Astronomy
Robert W. Clayton, Ph.D.
Geophysics
John M. Eiler, Ph.D.
Robert P. Sharp Professor of Geology and Professor of Geochemistry
Charles Elachi, Ph.D.
Electrical Engineering and Planetary Science
Kenneth A. Farley, Ph.D.
W. M. Keck Foundation Professor of Geochemistry
Woodward Fischer, Ph.D.
Geobiology
John P. Grotzinger, Ph.D.
Eleanor and John R. McMillan Professor of Geology
Michael C. Gurnis, Ph.D.
John E. and Hazel S. Smits Professor of Geophysics
Thomas H. Heaton, Ph.D.
Engineering Seismology
Donald V. Helmberger, Ph.D.
Geophysics
Andrew P. Ingersoll, Ph.D.
Planetary Science
Jennifer Jackson, Ph.D.
Mineral Physics
Joseph L. Kirschvink, Ph.D.
Nico and Marilyn Van Wingen Professor of Geobiology
Shrinivas R. Kulkarni, Ph.D.
John D. and Catherine T. MacArthur Professor of Astronomy and Planetary Science
Michael Lamb, Ph.D.
Geology
Nadia Lapusta, Ph.D.
Mechanical Engineering and Geophysics
Jared Leadbetter, Ph.D.
Environmental Microbiology
Dianne K. Newman, Ph.D.[1]
Biology and Geobiology
Victoria Orphan, Ph.D.
Geobiology
George R. Rossman, Ph.D.
Eleanor and John R. McMillan Professor of Mineralogy
Alex L. Sessions, Ph.D.
Geobiology
Mark Simons, Ph.D.
Geophysics
David J. Stevenson, Ph.D.
Marvin L. Goldberger Professor of Planetary Science

Joann M. Stock, Ph.D.
Geology and Geophysics
Edward M. Stolper, Ph.D., D.Sc.h.c.
Carl and Shirley Larson Provostial Chair; William E. Leonhard Professor of Geology
Paul O. Wennberg, Ph.D.
R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering
Brian P. Wernicke, Ph.D.
Chandler Family Professor of Geology
Yuk L. Yung, Ph.D.
Smits Family Professor of Planetary Science; Jet Propulsion Laboratory Research Scientist

[1] *Joint appointment with Howard Hughes Medical Institute*

Associate Professor

Christian Frankenberg, Ph.D.
Environmental Science and Engineering

Assistant Professors

Jean-Paul Ampuero Saenz, Ph.D.
Seismology
Konstantin Batygin, Ph.D.
Planetary Science
Simona Bordoni, Ph.D.
Environmental Science and Engineering
Bethany L. Ehlmann, Ph.D.
Planetary Science; Jet Propulsion Laboratory Research Scientist
Heather Knutson, Ph.D.
Planetary Science
Andrew F. Thompson, Ph.D.
Environmental Science and Engineering
Victor Tsai, Ph.D.
Geophysics
Zhongwen Zhan, Ph.D.
Geophysics

Lecturers

Kathryn Bikle, M.A.
Geology

Research Assistant Professor

Paul S. Nerenberg, Ph.D.
Planetary Science

Research Professor

Egill Hauksson, Ph.D.
Geophysics

Faculty Associate

Dimitri A. Papanastassiou, Ph.D.
Geochemistry

Moore Distinguished Scholar

Jon Blundy, Ph.D.
Geology

Visiting Associates

Piyush Agram, Ph.D.
Geophysics
Oded Aharonson, Ph.D.
Planetary Science
Mokhles Azer, Ph.D.
Geology
Carmen Boening, Ph.D.
Environmental Science and Engineering
Raul Castro Escamilla, Ph.D.
Geophysics
Elizabeth Cochran, Ph.D.
Geophysics
Max Coleman, Ph.D.
Geochemistry
Matthew Golombek, Ph.D.
Planetary Science
Robert W. Graves, Ph.D.
Geophysics
John M. Harris, Ph.D.
Geology
Kenneth W.Hudnut, Ph.D.
Geophysics
Hope Johnson, Ph.D.
Geobiology
Lucile M. Jones, Ph.D.
Geophysics
Yang Liu, Ph.D.
Geochemistry
Daniel J. McCleese, Ph.D.
Planetary Science

Charles E. Miller, Ph.D.
Environmental Science and Engineering
Meghan Miller, Ph.D.
Geophysics
Louis Moresi, Ph.D.
Geophysics
Paul Rosen, Ph.D.
Geophysics
Stanley P. Sander, Ph.D.
Planetary Science and Environmental Engineering Science
Joao Teixeira, Ph.D.
Environmental Science and Engineering
Geoffrey Toon, Ph.D.
Planetary Science
Joan Valentine, Ph.D.
Geobiology
Paulo Vasconcelos, Ph.D.
Geochemistry
Duane Waliser, Ph.D.
Planetary Science
Kenneth Williford, Ph.D.
Geobiology
Josh Willis, Ph.D.
Environmental Science and Engineering

Members of the Professional Staff

Michael B. Baker, Ph.D.
Geology
John R. Beckett, Ph.D.
Geology
Ma Chi, Ph.D.
Geochemistry
Joachim Genrich, Ph.D.
Geology
Yunbin Guan, Ph.D.
Geochemistry
Sally Newman, Ph.D.
Geology

Postdoctoral Scholars

Naofumi Aso, Ph.D.
Geophysics
Bjoern Benneke, Ph.D.
Planetary Science
Megan Bergkessel, Ph.D.
Geobiology
Maryjo Brounce, Ph.D.
Geology
Claire Bucholz, Ph.D.
O.K. Earl Postdoctoral Scholar, Geology
Hao Cao, Ph.D.
Planetary Science
Katherine S. Dawson, Ph.D.
Geobiology
Katherine Deck, Ph.D.
JCPA Prize Fellow
Peter Douglas, Ph.D.
Geochemistry
Courtney Dressing, Ph.D.
Sagan Postdoctoral Scholar
Heresh Fattahi, Ph.D.
Geophysics
Nicole Feldl, Ph.D.
Environmental Science and Engineering
Gregory Finkelstein, Ph.D.
Geophysics
Abigail Fraeman, Ph.D.
Texaco Prize Fellow; KISS Postdoctoral Fellow
Mariano Garcia Alonso, Ph.D.
Marie Curie Postdoctoral Scholar
Rebecca Greenberger, Ph.D.
Planetary Science
Roland Hatzenpichler, Ph.D.
Geobiology
James Hemp, Ph.D.
Geobiology
Jessica Hinojosa, Ph.D.
GPS Chair/AGEP Postdoctoral Scholar
Forrest Horton, Ph.D.
Geochemistry
Hsin-Hua Huang, Ph.D.
Geophysics
Xabier Iturbe, Ph.D.
Marie Curie Postdoctoral Scholar
Michelle Kim, Ph.D.
Environmental Science and Engineering
Yen-Ting Ko, Ph.D.
Geophysics
Catherine Macris, Ph.D.
Geochemistry
Georgy Manucharyan, Ph.D.
Stanback Postdoctoral Scholar
Monica Paola Martinez Ortiz, Ph.D.
Environmental Science and Engineering
Men-Andrin Meier, Ph.D.
Geophysics
Ross Mitchell, Ph.D.
Geology

Cajetan Neubauer, Ph.D.
Geobiology
Tran B. Nguyen, Ph.D.
NSF Fellow in Global Environmental Science
Anke Noelscher, Ph.D.
Environmental Science and Engineering
Marisa Palucis, Ph.D.
Geology
Salvatore Pascale, Ph.D.
Environmental Science and Engineering
Alexis Pasulka, Ph.D.
Geobiology
Erik Petigura, Ph.D.
Planetary Science
Camilo Ponton, Ph.D.
Geochemistry
Michael Poston, Ph.D.
Geochemistry
Uri Ryb, Ph.D.
Geochemistry
Silvan Scheller, Ph.D.
Geobiology
Juerg Schuler, Ph.D.
Geophysics
Oliver Shorttle, Ph.D.
Geochemistry
Min Sub Sim, Ph.D.
Geobiology
Connor Skennerton, Ph.D.
Geobiology
Derek Smith, Ph.D.
Geobiology
Nivedita Thiagarajan, Ph.D.
Dreyfus Fellow in Geochemistry
Mark Torres, Ph.D.
Texaco/AGEP Postdoctoral Scholar
Camille Viatte, Ph.D.
Environmental Science and Engineering
Huilin Wang, Ph.D.
Geophysics
Jessica Watkins, Ph.D.
GPS Chair/AGEP Postdoctoral Scholar
Reto Wijker, Ph.D.
Geobiology
Elizabeth Wilbanks, Ph.D.
Geobiology
Ting Yang, Ph.D.
Geophysics
Lingling Ye, Ph.D.
Postdoctoral Scholar in Geophysics
Han Yue, Ph.D.
Geophysics
Qiong Zhang, Ph.D.
Geophysics

Visitors

Jonathan Fraine, M.S.
Planetary Science
Shana Goffredi, Ph.D.
Geobiology
Martha House, Ph.D.
Geology
Robert Housley, Ph.D.
Geochemistry
Renyu Hu, Ph.D.
Planetary Science
Emily Lakdawalla, M.Sc.
Planetary Science
Shawn McGlynn, Ph.D.
Geobiology
Vijay Natraj, Ph.D.
Planetary Science
Jay Pasachoff, Ph.D.
Planetary Science
Patricia Persaud, Ph.D.
Geophysics
Avi Shporer, Ph.D.
Planetary Science
Yanhua Shuai, Ph.D.
Geochemistry
Wolfgang Sturhahn, Ph.D.
Geophysics

Division of the Humanities and Social Sciences

Jean-Laurent Rosenthal, *Chair*
Federico Echenique, *Executive Officer for the Social Sciences*
Catherine Jurca, *Executive Officer for the Humanities*

Professors Emeriti

Louis Breger, Ph.D.
Psychoanalytic Studies
David M. Grether, Ph.D.
Frank J. Gilloon Professor of Economics
Daniel J. Kevles, Ph.D.
J. O. and Juliette Koepfli Professor of the Humanities
Jenijoy La Belle, Ph.D.
English
Oscar Mandel, Ph.D.
Literature
Robert A. Rosenstone, Ph.D.
History
Thayer Scudder, Ph.D.
Anthropology
Annette J. Smith, Ph.D.
Literature
James F. Woodward, Ph.D.
J. O. and Juliette Koepfli Professor of the Humanities

Associate Professor Emeritus

Heinz E. Ellersieck, Ph.D.
History

Lecturers Emeriti

Lee F. Browne, M.S.
Education
Shirley A. Marneus, M.A.
Theater Arts

Professors

Ralph Adolphs, Ph.D.
Bren Professor of Psychology and Neuroscience and Professor of Biology
R. Michael Alvarez, Ph.D.
Political Science
Kim C. Border, Ph.D.
Economics
John Brewer, Ph.D.
Eli and Edye Broad Professor of Humanities and Social Sciences and Professor of History and Literature
Warren C. Brown, Ph.D.
History
Jed Z. Buchwald, Ph.D.
Doris and Henry Dreyfuss Professor of History
Colin F. Camerer, Ph.D.
Robert Kirby Professor of Behavioral Economics
Fiona Cowie, Ph.D.
Philosophy
Jaksa Cvitanic, Ph.D.
Richard N. Merkin Professor of Mathematical Finance
Tracy K. Dennison, Ph.D.
History
Frederick Eberhardt, Ph.D.
Philosophy
Federico Echenique, Ph.D.
Economics
Jean E. Ensminger, Ph.D.
Edie and Lew Wasserman Professor of Social Sciences
Mordechai Feingold, D.Phil.
History
Kevin M. Gilmartin, Ph.D.
English
Dehn Gilmore, Ph.D.
English
Kristine Haugen, Ph.D.
English
Christopher R. Hitchcock, Ph.D.
J. O. and Juliette Koepfli Professor of Philosophy
Philip T. Hoffman, Ph.D.
Rea A. and Lela G. Axline Professor of Business Economics and Professor of History
Catherine Jurca, Ph.D.
English
Jonathan N. Katz, Ph.D.
Kay Sugahara Professor of Social Sciences and Statistics
D. Roderick Kiewiet, Ph.D.
Political Science
Diana L. Kormos-Buchwald, Ph.D.
History
J. Morgan Kousser, Ph.D.
William R. Kenan, Jr. Professor of History and Social Science
John O. Ledyard, Ph.D., D.Lit.h.c.
Allen and Lenabelle Davis Professor of Economics and Social Sciences

John P. O'Doherty, D.Phil.
Psychology
Peter C. Ordeshook, Ph.D.
Political Science
Thomas R. Palfrey, Ph.D.
Flintridge Foundation Professor of Economics and Political Science
George W. Pigman III, Ph.D.
English
Charles R. Plott, Ph.D., D.Lit.h.c., D.h.c.
William D. Hacker Professor of Economics and Political Science
Steven R. Quartz, Ph.D.
Philosophy
Antonio Rangel, Ph.D.
Bing Professor of Neuroscience, Behavioral Biology, and Economics
Richard Roll, Ph.D.
Linde Institute Professor of Finance
Jean-Laurent Rosenthal, Ph.D.
Rea A. and Lela G. Axline Professor of Business Economics
Robert P. Sherman, Ph.D.
Economics and Statistics
Matthew S. Shum, Ph.D.
Economics
Erik Snowberg, Ph.D.
Economics and Political Science
Cindy Weinstein, Ph.D.
English
Nicolas Wey-Gomez, Ph.D.
History
Leeat Yariv, Ph.D.
Economics

Associate Professors

Michael Ewens, Ph.D.
Economics
Alexander V. Hirsch, Ph.D.
Political Science

Assistant Professors

Marina Agranov, Ph.D.
Economics
Matthew L. Elliott, Ph.D.
Economics
Benjamin J. Gillen, Ph.D.
Economics
Christopher Hunter, Ph.D.
English
Jennifer Jahner, Ph.D.
English
Lawrence J. Jin, Ph.D.
Finance
Katrina Ligett, Ph.D.
Computer Science and Economics
Gideon Manning, Ph.D.
Philosophy
Kota Saito, Ph.D.
Economics
Omer Tamuz, Ph.D.
Economics

Ahmanson Postdoctoral Instructor
Charles T. Sebens, Ph.D.
Philosophy

Jessen Postdoctoral Instructor
Keith D. Pluymers, Ph.D.
History

Weisman Postdoctoral Instructors

Benjamin A. Saltzman, Ph.D.
English

Lecturers

Elizabeth Abrams Rich, Ph.D.
Anthopology
Andreas Aebi, Ph.D.
German
Gloria Arjona, Ph.D.
Spanish
Tari Awipi, Ph.D.
Psychology
Shelley M. Bennett, Ph.D.
Art History
Christine M. Daley, Ph.D.
English
Daniel A. Garcia, M.A.
Spanish
Merrill Joan Gerber, M.A.
Creative Writing
Judith Hall, M.A.
Creative Writing
Susanne E. Hall, Ph.D.
English
Ritsuko Hirai, Ph.D.
Japanese
Kayoko Hirata, Ph.D.
Japanese

Richard E. Kipling, M.A.
Journalism
Trevor C. Merrill, Ph.D.
French
Feng-Ying Ming, Ph.D.
Chinese
Thomas A. Neenan, M.F.A.
Music
Christiane H. Orcel, Ph.D.
French
Lynn Paul, Ph.D.
Psychology
Oana Tudusciuc, Ph.D.
Psychology
Shiing-wu Wang, Ph.D.
Accounting
Xiangyun Wang, Ph.D.
Chinese
Kenneth Winston, Ph.D.
Economics
Juliann Kay Wolfgram, Ph.D.
Art History

Moore Distinguished Scholar

Robert J. Barro, Ph.D.
Economics
Paul W. Rhode, Ph.D.
Economics

Francis Bacon Visiting Professor
Jurgen Renn, Ph.D.
History

Eleanor Searle Visiting Professor

Asif Siddiqi, Ph.D.
History

Research Assistant Professor (formerly Senior Research Fellow)

Maura Dykstra, Ph.D.
History
Dennis Lehmkuhl, Ph.D.
Philosophy
Sarah Levine-Gronningsater, Ph.D.
History

Visiting Professors

Bradford Cornell, Ph.D.
Finance
Albert F. Park, Ph.D.
Economics

Visiting Associates

Jasmina Arifovic, Ph.D.
Economics
Peter Bossaerts, Ph.D.
Finance
Martin Chalifour
Humanities
John Clithero, Ph.D.
Neuroeconomics
Stefano O. Condorelli, Ph.D.
Economics
Jernej Copic, Ph.D.
Economics
Mikael Cozic, Ph.D.
Economics
Alexandre Dube, Ph.D.
History
Amanda Y. Friedenberg, Ph.D.
Economics
Cora Gilroy-Ware, Ph.D.
Art History
Mark Graves, Ph.D.
Psychology
Jens Grosser, Ph.D.
Economics
John L. Heilbron, Ph.D.
History
Steve Hindle, Ph.D.
History
Giora Hon, Ph.D.
History
Sungook Hong, Ph.D.
History
Rene Hurlemann, Ph.D.
Psychology
Jozsef Illy, Ph.D.
History
Daniel Kennedy, Ph.D.
Neuroscience
Anne Kox, Ph.D.
History
Ruth Lorand, Ph.D.
Philosophy
Barbara Oberg, Ph.D.
History
Julie Park, Ph.D.
English
Christina Ramirez, Ph.D.
Economics
Robert C. Ritchie, Ph.D.
History

Brian W. Rogers, Ph.D.
Social Science
Ajay Bhaskar Satpute, Ph.D.
Psychology
Wolfram Schultz, Ph.D.
Neuroscience
Betsy Sinclair, Ph.D.
Social Science
Michael L. Spezio, Ph.D.
Psychology
Noel M. Swerdlow, Ph.D.
History
Issachar Unna, Ph.D.
History
Shuo Wang, Ph.D.
Neuroscience

Visitors

Marco Giovanelli, Ph.D.
Philosophy
Uri M. Maoz, Ph.D.
Neural Computation

Member of the Professional Staff

Ze'ev Rosenkranz, M.L.S.

Postdoctoral Scholars

Jeffrey Cockburn, Ph.D.
Neuroscience
Sven Collette, Ph.D.
Neuroscience
Ahrash Dianat, Ph.D.
Economics
Julien Dubois, Ph.D.
Neuroscience
Giovanni Gentile, Ph.D.
Neuroeconomics
Duk Gyoo Kim, Ph.D.
Economics
Sang Wan Lee, Ph.D.
Neuroscience
Wolfgang Pauli, Ph.D.
Psychology and Neuroscience
Eva Pool, Ph.D.
Neuroscience
Robert Spunt, Ph.D.
Social Psychology
Damian Stanley, Ph.D.
Neuroeconomics
Shinsuke Suzuki, Ph.D.
Neuroscience
Anita Tusche, Ph.D.
Neuroeconomics

Division of Physics, Mathematics and Astronomy

Fiona A. Harrison, *Kent and Joyce Kresa Leadership Chair*
Anthony C. S. Readhead, *Director, Owens Valley Radio Observatory*
Gil Refael, *Executive Officer for Physics*
George Helou, *Executive Director, Infrared Processing and Analysis Center*
Shrinivas Kulkarni, *Director, Caltech Optical Observatories*
David H. Reitze, *Executive Director, LIGO Laboratory (Laser Interferometer Gravitational-Wave Observatory)*
Sunil Golwala, *Director, Caltech Submillimeter Observatory*
Nai-Chang Yeh, *Codirector, Kavli Nanoscience Institute*
Dinakar Ramakrishnan, *Executive Officer for Mathematics*
E. Sterl Phinney, *Executive Officer for Astronomy*
B. Thomas Soifer, Director *Spitzer Science Center*

Professors Emeriti

Tom M. Apostol, Ph.D.
Mathematics
Michael Aschbacher, Ph.D.
Shaler Arthur Hanisch Professor of Mathematics
Barry C. Barish, Ph.D., Laurea h.c.
Ronald and Maxine Linde Professor of Physics
Charles A. Barnes, Ph.D.
Physics
Felix H. Boehm, Ph.D.
William L. Valentine Professor of Physics
Marshall H. Cohen, Ph.D.
Astronomy
Richard A. Dean, Ph.D.
Mathematics
Ronald W. P. Drever, Ph.D.
Physics
Steven C. Frautschi, Ph.D.
Theoretical Physics
Murray Gell-Mann, Ph.D., Sc.D.h.c., D.Sc.h.c., Nobel Laureate
Robert Andrews Millikan Professor of Theoretical Physics
Peter M. Goldreich, Ph.D.
Lee A. DuBridge Professor of Astrophysics and Planetary Physics
David L. Goodstein, Ph.D.
Frank J. Gilloon Distinguished Teaching and Service Professor and Professor of Physics and Applied Physics
Gary A. Lorden, Ph.D.
Mathematics
W. A. J. Luxemburg, Ph.D.
Mathematics
Charles W. Peck, Ph.D.
Physics
Thomas G. Phillips, D.Phil.
John D. MacArthur Professor of Physics
Jerome Pine, Ph.D.
Physics
Anthony C. S. Readhead, Ph.D.
Robinson Professor of Astronomy
Maarten Schmidt, Ph.D., Sc.D.
Francis L. Moseley Professor of Astronomy
John H. Schwarz, Ph.D.
Harold Brown Professor of Theoretical Physics
Kip S. Thorne, Ph.D., D.Sc.h.c., D.h.c., L.H.D.h.c.
Richard P. Feynman Professor of Theoretical Physics
Rochus E. Vogt, Ph.D.
R. Stanton Avery Distinguished Service Professor and Professor of Physics
David B. Wales, Ph.D.
Mathematics
Ward Whaling, Ph.D.
Physics
Richard M Wilson, Ph.D.
Mathematics

Senior Research Associate Emeritus

Petr Vogel, Ph.D.
Physics

Professors

Rana Adhikari, Ph.D.
Physics
Jason Alicea, Ph.D.
Theoretical Physics
James J. Bock, Ph.D.
Physics

Yanbei Chen, Ph.D.
Physics
Judith G. Cohen, Ph.D.
Kate Van Nuys Professor of Astronomy
Michael C. Cross, Ph.D.
Theoretical Physics
S. George Djorgovski, Ph.D.
Astronomy
James P. Eisenstein, Ph.D.
Frank J. Roshek Professor of Physics and Applied Physics
Bradley W. Filippone, Ph.D.
Physics
Matthias Flach, Ph.D.
Mathematics
Rupert Frank, Ph.D.
Mathematics
Sunil Golwala, Ph.D.
Physics
Thomas Graber, Ph.D.
Mathematics
Sergei Gukov, Ph.D.
Theoretical Physics and Mathematics
Fiona A. Harrison, Ph.D., D.techn.h.c.
Benjamin M. Rosen Professor of Physics and Astronomy
Lynne Anne Hillenbrand, Ph.D.
Astronomy
David G. Hitlin, Ph.D.
Physics
Anton Kapustin, Ph.D.
Earle C. Anthony Professor of Theoretical Physics and Mathematics
Nets Katz, Ph.D.
Mathematics
Alexander S. Kechris, Ph.D., D.h.c.
Mathematics
H. Jeff Kimble, Ph.D., D.Sc.h.c.
William L. Valentine Professor and Professor of Physics
Alexei Kitaev, Ph.D.
Ronald and Maxine Linde Professor of Theoretical Physics & Mathematics
Shrinivas R. Kulkarni, Ph.D.
John D. and Catherine T. MacArthur Professor of Astronomy and Planetary Science
Kenneth G. Libbrecht, Ph.D.
Physics
Nikolai G. Makarov, Ph.D.
Richard Merkin Distinguished Professor of Mathematics
Elena Mantovan, Ph.D.
Mathematics
Matilde Marcolli, Ph.D.
Mathematics
Vladimir Markovic, Ph.D.
John D. MacArthur Professor of Mathematics
D. Christopher Martin, Ph.D.
Physics
Olexei Motrunich, Ph.D.
Theoretical Physics
Harvey B. Newman, Sc.D.
Physics
Yi Ni, PhD.
Mathematics
Hiroshi Ooguri, Ph.D.
Fred Kavli Professor of Theoretical Physics and Mathematics
Christian Ott, Ph.D.
Theoretical Astrophysics
E. Sterl Phinney, Ph.D.
Theoretical Astrophysics
H. David Politzer, Ph.D., Nobel Laureate
Richard Chace Tolman Professor of Theoretical Physics
Frank C. Porter, Ph.D.
Physics
John P. Preskill, Ph.D.
Richard P. Feynman Professor of Theoretical Physics
Thomas A. Prince, Ph.D.
Physics
Eric M. Rains, Ph.D.
Mathematics
Dinakar Ramakrishnan, Ph.D.
Taussky-Todd-Lonergan Professor of Mathematics
Gil Refael, Ph.D.
Theoretical Physics
Thomas F. Rosenbaum Ph.D.
Physics
Michael L. Roukes, Ph.D.
Robert M. Abbey Professor of Physics, Applied Physics and Bioengineering
Anneila I. Sargent, Ph.D., D.Sc.h.c.
Ira S. Bowen Professor of Astronomy
Axel Scherer, Ph.D.
Bernard A. Neches Professor of Electrical Engineering, Applied Physics and Physics
Nicholas Z. Scoville, Ph.D.
Francis L. Moseley Professor of Astronomy

Barry M. Simon, Ph.D., D.Sc.h.c.
IBM Professor of Mathematics and Theoretical Physics
B. Thomas Soifer, Ph.D.
Physics
Maria Spiropulu, Ph.D.
Physics
Charles C. Steidel, Ph.D.
Lee A. DuBridge Professor of Astronomy
Edward C. Stone, Ph.D., D.Sc.h.c.
David W. Morrisroe Professor of Physics
Alan J. Weinstein, Ph.D.
Physics
Mark B. Wise, Ph.D.
John A. McCone Professor of High Energy Physics
Nai-Chang Yeh, Ph.D.
Physics
Ahmed H. Zewail, Ph.D., D.Sc.h.c., D.h.c., D.Univ.h.c., D.Phil.h.c., LL.D.h.c., M.D.h.c., Nobel Laureate
Linus Pauling Professor of Chemistry and Professor of Physics
Jonas Zmuidzinas, Ph.D.
Merle Kingsley Professor of Physics

Associate Professors

Dimitri P. Q. Mawet, Ph.D.
Astronomy
Xinwen Zhu Ph.D.
Mathematics

Assistant Professors

Xie Chen, Ph.D.
Theoretical Physics
Clifford Cheung, Ph.D.
Theoretical Physics
Gregg W. Hallinan, Ph.D.
Astronomy
Philip F. Hopkins, Ph.D.
Theoretical Astrophysics
David Hsieh, Ph.D.
Physics
Mansi Kasliwal, Ph.D.
Astronomy
Evan Kirby, Ph.D.
Astronomy
Ryan Patterson, Ph.D.
Physics

Instructors

Adam Sheffer, Ph.D.
Harry Bateman, Mathematics
Semra Demirel, Ph.D.
Harry Bateman Research Instructor in Mathematics
Farzad Fathizadeh, Ph.D.
Olga Taussky-Todd, Mathemathics
Christopher M. Ormerod, Ph.D.
Olga Taussky and John Todd Research Instructor in Mathematics
Elwadura Prabath Silva, Ph.D.
Harry Bateman, Mathematics
Paolo Solis, Ph.D.
Olga Taussky-Todd, Mathemathics
Pei-Yu Tsai, Ph.D.
Olga Taussky and John Todd Research Instructor in Mathematics
Faramarz Vafaee, Ph.D.
Harry Bateman, Mathematics

Lecturers

Eric D. Black, Ph.D.
Physics
Sergi Hildebrandt, Ph.D.
Physics
Chris Mach, B.S.
Physics
Hien Nguyen, Ph.D.
Physics
Frank Rice, M.S.
Physics
Erik Verlinde, Ph.D.
High Energy Physics

Research Professors/ Senior Research Associates

John Carpenter, Ph.D.
Astronomy
Sean Carroll, Ph.D.
Physics
Bertrand Echenard, Ph.D.
Physics
George Helou, Ph.D.
Physics
Richard A. Mewaldt, Ph.D.
Physics
Timothy J. Pearson, Ph.D.
Radio Astronomy
David H. Reitze, Ph.D.
Physics
Mark Scheel, Ph.D.
Physics

Research Assistant Professors/ Senior Research Fellows

Majid Hadian-Jazi
Scott Russell Johnson, Mathematics
Yu Nakayama, Ph.D.
Sherman Fairchild Fellow in Theoretical Physics
Gang Zhou, Ph.D.
Mathematics

Senior Faculty Associates

Curt Cutler, Ph.D.
Physics

Faculty Associate

Todd Gaier, Ph.D.
Physics

Visiting Associates

Paolo Aluffi, Ph.D.
Mathematics
Jorgen Andersen, Ph.D.
Mathematics
Joseph Bernstein, Ph.D.
Mathematics
Emanuele Berti, Ph.D.
Physics
Andrew Blain, Ph.D.
Astronomy
Jie Bao, Ph.D.
Physics
Charles Matt Bradford, Ph.D.
Physics
Todd Brun, Ph.D.
Physics
Alessandra Buonanno, Ph.D.
Physics
Goutam Chattopadhyay, Ph.D.
Physics
Michael John Collins, Ph.D.
Mathematics
Asantha Cooray, Ph.D.
Physics
Brendan P. Crill, Ph.D.
Physics
Peter Day, Ph.D.
Physics
Stanley Deser, Ph.D.
Theoretical Physics
Luc Dessart, Ph.D.
Theoretical Astrophysics
Olivier Dore´, Ph.D.
Theoretical Astrophysics
Darren Dowell, Ph.D.
Physics
Robert V. Duncan, Ph.D.
Physics
Tim Eifler, Ph.D.
Physics
Gerald Eigen, Ph.D.
Physics
Richard Ellis, Ph.D.
Astronomy
Manuel Endres, Ph.D.
Physics
Wolfgang Fink, Ph.D.
Physics
Thomas George, Ph.D.
Physics
Paul F. Goldsmith, Ph.D.
Astronomy
Gabriela Gonzalez, Ph.D.
Physics
Krzysztof Gorski, Ph.D.
Physics
Keith J.B. Grainge, Ph.D.
Physics
Herold R. Gustafson, Ph.D.
Physics
Inseob Hahn, Ph.D.
Physics
Stephen W. Hawking, Ph.D.
Sherman Fairchild Distinguished Scholar
Martin Houde, Ph.D.
Physics
Bing Jiang, Ph.D.
Physics
Mansi Manoj Kasliwal, Ph.D.
Astronomy
Jin Koda, Ph.D.
Physics
Joseph W. Lazio, Ph.D.
Astronomy
Richard A. M. Lee, Ph.D.
Physics
Erik Leitch, Ph.D.
Astronomy
Daniel A. Lidar, Ph.D.
Theoretical Physics
Ron Y. Lifshitz, Ph.D.
Physics
Dariusz Lis, Ph.D.
Physics

Geoffrey Lovelace, Ph.D.
Physics
Walid Majid, Ph.D.
Experimental Astrophysics
Peter V. Mason, Ph.D.
Physics
Steve McGuire, Ph.D.
Physics
Simona Mei, Ph.D.
Astronomy
David Meier, Ph.D.
Astronomy
Hrushikesh Mhaskar, Ph.D.
Mathematics
Roger Mong, Ph.D.
Theoretical Physics
Hien T. Nguyen, Ph.D.
Physics
Shouleh Nikzad, Ph.D.
Astrophysics
Iosif Papadakis, Ph.D.
Physics
Robert Penner, Ph.D.
Mathematical and Theoretical Physics
Pavel Fileviez Perez, Ph.D.
Physics
Michael Ramsey-Musolf, Ph.D.
Physics
Jocelyn S. Read, Ph.D.
Theoretical Astrophysics
Paul Renteln, Ph.D.
Mathematics
Jason Rhodes, Ph.D.
Astronomy
Alton D. Romig, Ph.D.
Physics
Ira Zvi Rothstein, Ph.D.
Physics
John Elie Sader, Ph.D.
Physics
Re'em Sari, Ph.D.
Astrophysics
Bangalore Sathyaprakash, Ph.D.
Physics
Janet D. Scheel, Ph.D.
Physics
Robert Schofield, Ph.D.
Physics
Yoav Segev, Ph.D.
Mathematics
Eugene Serabyn, Ph.D.
Physics
Hongsheng Shi
Physics
David H. Shoemaker, Ph.D.
LIGO
Kirill Shtengel, Ph.D.
Physics
Mark Stalzer, Ph.D.
Computational Science
Piotr Sulkowski, Ph.D.
Physics
Saul Teukolsky, Ph.D.
Theoretical Astrophysics
Manuel Tiglio, Ph.D.
Physics
Edwin Upchurch, Ph.D.
Astronomy
Michele Vallisneri, Ph.D.
Physics
Steven J. van Enk, Ph.D.
Physics
Otmar Venjakob, Ph.D.
Mathematics
Joaquin D. Vieira,
Astronomy
Fellix von Oppen, Ph.D.
Theoretical Physics
Michael Werner, Ph.D.
Astrophysics
Mark E. Wiedenbeck, Ph.D.
Physics
Anna K. Wienhard, Ph.D.
Mathematics
Joyce Wong, Ph.D.
Physics
Guanglian Zhang, Ph.D.
Mathematics

Members of the Professional Staff

Rachel Akeson, Ph.D.
Stuart Anderson, Ph.D.
Philip Appleton, Ph.D
Jessica Arlett, Ph.D.
Lee Armus, Ph.D.
Thomas Barlow, Ph.D.
Bruce Berriman, Ph.D.
James Kent Blackburn, Ph.D.
Andrew Boden, Ph.D.
Julian Bunn, Ph.D.
Peter L. Capak, Ph.D.
Sean J. Carey, Ph.D
Robert W. Carr, M. Phil.
Ranga Ram Chary, Ph.D.
David R. Ciardi, Ph.D.
Kieran A. Cleary, Ph.D.
Christina M. S. Cohen, Ph.D.
Walter R. Cook, Ph.D.
Dennis C. Coyne, M.S.
Alan C. Cummings, Ph.D.
Roc Cutri, Ph.D.

Richard Dekany, Ph.D.
Dario Fadda, Ph.D.
Chung Wah (Warren) Fon, Ph.D.
Valery Frolov, Ph.D
Joseph A. Giaime, Ph.D.
Matthew Graham, Ph.D.
Carl Grillmair, Ph.D.
Eric K. Gustafson, Ph.D
Dale Ingram, M.S.
Keita Kawabe, Ph.D.
Davy Kirkpatrick, Ph.D.
Nicholas Konidarias, Ph.D.
Michael Landry, Ph.D.
Albert Lazzarini, Ph.D.
Richard A. Leske, Ph.D.
Phillip E. Lindquist, Eng.
Nanyao Lu, Ph.D.
William Mahoney, Ph.D.
Keith Matthews, M.S.
Joseph Mazzarella, Ph.D.
Gregory Mendell, Ph.D.
Rafael Millan-Gabet, Ph.D.
Anna Marie Moore, Ph.D.
Patrick Morris, Ph.D.
Patrick Morrissey, Ph.D.
Patrick Ogle, Ph.D.
J. E. Brian O'Reilly, Ph.D.
Fredrick J. Raab, Ph.D.
Simon J.E. Radford, Ph.D.
Luisa M. Rebull, Ph.D.
Alan P. Rice, B.S.
Norna A. Robertson, Ph.D.
Gary H. Sanders, Ph.D.
Richard Savage, Ph.D.
Patrick Shopbell, Ph.D.
David Shupe, Ph.D.
Daniel Sigg, Ph.D.
Nancy Silbermann, Ph.D.
Roger Smith, B.E.
Gordon Squires, Ph.D.
John Stauffer, Ph.D.
Lisa Storrie-Lombardi, Ph.D.
Jason Surace, Ph.D.
Harry Teplitz, Ph.D.
Schuyler Van Dyk, Ph.D.
Yun Wang, Ph.D.
Stanley E. Whitcomb, Ph.D.
Roy Williams, Ph.D.
David P. Woody, Ph.D.
Hiroaki Yamamoto, Ph.D.
Lin Yan, Ph.D.
Ren-Yuan Zhu, Ph.D.
Michael Zucker, Ph.D.
John Zweizig, Ph.D.

Senior Postdoctoral Scholars

Stephen Bourke, Ph.D.
Astronomy
Sean Couch, Ph.D.
Physics
William C. Griffith, Ph.D.
Experimental Physics
Nicholas P. Konidaris II, Ph.D.
Astronomy Instrumentation
Maurizio Pierini, Ph.D.
High Energy Physics
Larry Price, Ph.D.
Physics
Raquel Rodriguez Monje
Physics
Jack Sayers, Ph.D.
Physics
Esayas Shume, Ph.D.
Astronomy
Ulrich Sperhake, Ph.D.
Physics
Christina V. Torres, Ph.D.
Physics
Marco P. Viero, Ph.D.
Physics
Michael Zemcov, Ph.D.
Physics

Postdoctoral Scholars

Margareta Ackerman, Ph.D.
Center for the Mathematics of Information
Haipeng An, Ph.D.
John McCone, Theoretical Physics
Arthur Apresyan, Ph.D.
Tolman, Experimental Physics
Stuart Mark Aston, Ph.D.
Physics
Mehrtash Babadi, Ph.D.
Physics
Christopher Backhouse, Ph.D.
Particle Physics
Nairn R. Baliber, Ph.D.
Astronomy
Ning Bao, Ph.D.
Lee DuBridge, Theoretical Physics
Charles Edouard Jean Luc
Stephane Bardyn, Ph.D
Physics
Kirk R. Bays, Ph.D.
High Energy Physics
Eric C. Bellm, Ph.D.
Astrophysics
Mario Andrea (Mario) Berta, Ph.D.
Theoretical Physics

Murray Brightman, Ph.D.
Physics
Drew Clausen, Ph.D.
Lee DuBridge, Theoretical Physics
Abigail Tinney Crites, Ph.D.
W. M. Keck Inst., Physics
Yu (Sophia) Dai, Ph.D.
Astrophysics
Vladimir Dergachev, Ph.D.
Physics
Katherine Dooley, Ph.D.
Physics
Sheila Dwyer, Ph.D.
Physics
Andrew Essin, Ph.D.
Physics
Glen B. Evenbly, Ph.D.
Sherman Fairchild, Quantum Computing/ Condensed Matter
Pol Forn-Diaz, Ph.D.
Quantum Optics
Anamaria Effler, Ph.D.
Physics
Krzysztof Findeistein, Ph.D.
Astronomy
Felix Fuerst, Ph.D.
Physics
Jim Fuller, Ph.D.
Lee DuBridge, Theoretical Physics
Chad Galley, Ph.D.
Physics
Viktoriya Giryanskaya, Ph.D.
Physics
David Gonzalez Ovejero, Ph.D.
Astrophysics
Sarang Gopalakrishnan, Ph.D.
Burke, Theoretical Physics
David Gosset, Ph.D.
Sherman Fairchild, Theoretical Physics
Steven Hailey-Dunsheath, Ph.D.
Tolman, Experimental Physics
Erika Hamden, Ph.D.
Physics
John Harter, Ph.D.
Physics
Christopher Hayward, Ph.D.
Theoretical Astrophysics
Daniel Hemberger, Ph.D.
Physics
Kari Hodge, Ph.D.
Physics
Lotte Hollands, Ph.D.
Physics
Kiwami Izumi, Ph.D.
Physics
Jitse Joannes (Jan), Ph.D.
Mathematics
Torsten Karzig, Ph.D.
Condensed Matter Physics
Eyal Kenig, Ph.D.
Physics
Phil Korngut, Ph.D.
Physics
Attila Kovacs, Ph.D.
Physics
Gillian Kyne, Ph.D.
Physics
Olivier Landon-Cardinal, Ph.D.
Theoretical Physics
Lauranne Lanz, Ph.D.
Astrophysics
Chung Lun (Alan) Lai, Ph.D.
Mathematics
Tjonnie Guang Feng Li, Ph.D.
Physics
Martin Lueker, Ph.D.
Physics
Vyacheslav Lysov, Ph.D.
Sherman Fairchild, Theoretical Physics
Mingwu Lu, Ph.D.
Physics
Denis Martynov, Ph.D.
Physics
Daniel C. Masters, Ph.D.
Astrophysics
Christopher M. McKenney, Ph.D.
Physics
Jason Melbourne, Ph.D.
Physics, IPAC
Ryan Mishmash, Ph.D.
Lee DuBridge, Theoretical Physics
Lorenzo Moncelsi, Ph.D.
Physics
Christine Moran, Ph.D.
Numerical Relativity
Chiara Mingarelli, Ph.D.
Marie Curie, Astrophysics
David Fabian Mross, Ph.D.
Physics
Muhammad Mujeeb-U-Rahman, Ph.D.
Physics
Atsushi Nishizawa, Ph.D.
Physics
Roger O'Brient, Ph.D.
Experimental Physics
Fernando M. Pastawski, Ph.D.
heoretical Physics
Johanner Pollanen, Ph.D.
Physics

Stephen Privitera, Ph.D.
Physics
David Radice, Ph.D.
Sherman Fairchild, Theoretical Physics
Vikram Ravi, Ph.D.
Millikan, Astronomy
Luke Roberts, Ph.D.
Einstein, Theoretical Physics
Leslie Rodgers, Ph.D.
Hubble, Astronomy
Observational Cosmology
Ryan de Rosa, Ph.D.
Physics
Eric Sage, Ph.D.
Physics
Patricia Schmidt, Ph.D.
Physics
Andre da Silva Schneider, Ph.D.
Theoretical Astrophysics
Simon Slutsky, Ph.D.
Experimental Physics
Rory J.E. Smith, Ph.D.
Physics
Justin Song, Ph.D.
Sherman Fairchild, Theoretical Physics
Jonathan Squire, Ph.D.
Burke, Theoretical Physics
Bryan Steinbach, Ph.D.
Physics
Charles L. Steinhardt, Ph.D.
Astronomy
Natalia Stroch, Ph.D.
Theoretical Astrophysics
Christopher M. Swank, Ph.D.
Physics
Lian Tao, Ph.D.
Physics
Paul Kristan (Kristan) Temme, Ph.D.
Theoretical Physics
Shriharsh Tendulkar, Ph.D.
Physics
Jaroslav Trnka, Ph.D.
Lee, Theoretical Physics
Gabriele Vajente, Ph.D.
Physics
Harish Vedantham, Ph.D.
Tolman, Experimental Physics
Jean-Roch Vlimant, Ph.D.
High Energy Physics
Ling Wang, Ph.D.
Physics
Andrew R. Wetzel, Ph.D.
Astrophysics
Hao-Yi (Heidi) Wu, Ph.D.
Physics
Zhongtao Wu, Ph.D.
Simons, Mathematics
Si Xie, Ph.D.
Millikan Experimental Physics
Yue Zhang, Ph.D.
Theoretical Physics
Liuyan Zhao, Ph.D.
Tolman, Experimental Physics
Adi Zitrin, Ph.D.
Hubble, Astronomy

Center for Data-Driven Discovery

George Djorgovsky
Director

Information Management Systems and Services

Rich Fagen, B.A.
Chief Information Officer

Directorate

Beverly Allen, M.B.A.
Glenn W. Bach, M.S.
RuthAnne Bevier, M.L.I.S.
Dawn Boyd, B.S.
Bradley Cain, J.D.
Ron Kong, M.S.
Robert Logan, B.S.
Leslie Maxfield, M.S.

Jet Propulsion Laboratory

Administered by Caltech for the National Aeronautics and Space Administration

Charles Elachi, *Director*
Larry D. James, *Deputy Director*

Executive Council

A. Blaine Baggett
Director for Communications and Education
Diane L. Evans
Director for Earth Science and Technology
David Gallagher
Director for Astronomy, Physics, and Space Technology
Cozette M. Hart
Director for Human Resources
Chris P. Jones
Associate Director for Flight Projects and Mission Success
Janis L. Chodas
Director for Office of Safety and Mission Success
Fuk K. Li
Manager, Mars Exploration Program Office and Director for Mars Exploration
Leslie L. Livesay
Director for Engineering and Science
Daniel J. McCleese
Chief Scientist
Keyur C. Patel
Director for Interplanetary Network
Brian Muirhead
Chief Engineer
Firouz M. Naderi
Director for Solar System Exploration
Richard P. O'Toole
Manager, Office of Legislative Affairs
Steve Proia
Chief Financial Officer and Director for Business Operations
James J. Rinaldi
Chief Information Officer and Director for Information Technology
Victoria D. Stratman
Caltech General Counsel
Jakob van Zyl
Associate Director for Project Formulation and Strategy
Jonas Zmuidzinas
Chief Technologist

Library Services

Administration
Kristin Antelman
University Librarian
Robin Izon
Library Operations Administrator
Catherine Geard
Library Business Administrator

Department Heads
Gail P. Clement
Head of Research Services
Stephen Davison
Head of Digital Library Development
David McCaslin
Head of Access & Fulfillment Services
To be announced
Head of Archives & Special Collections

Staff and Faculty Consultation Center

Linda Krippner, Psy.D., *Director*

Student Affairs

Joseph E. Shepherd
Vice President for Student Affairs
Felicia A. Hunt
Assistant Vice President for Equity, Accessibility, and Inclusion Initiatives, and Title IX Coordinator
Douglas C. Rees
Dean of Graduate Studies
Erik C. Snowberg
Master of Student Houses
To be Announced
Dean of Undergraduate Students
Barbara C. Green
Interim Dean of Undergraduate Students
Betsy Mitchell
Director of Athletics, Recreation, and Physical Education

Kevin Austin
Executive Director of Health and Counseling Services
Don A. Crewell
Director of Student Financial Aid
Cindy de Mesa
Administrator, Performing and Visual Arts Programs
Maria A. Katsas
Acting Director of Housing
Tom Mannion
Senior Director Student Activities and Programs
Stuart Miller
Medical Director of Health Services

Mary N. Morley
Registrar
Lesley Nye
Associate Dean of Undergraduate Students
Dimitris A. Sakellariou
Chief Business Administrator
Lauren Stolper
Director of Fellowships Advising and Study Abroad, and Career Development Center
Jonathan Webster
Senior Director of Dining Services
Jarrid Whitney
Executive Director of Admissions and Financial Aid

OFFICERS AND FACULTY

University of California = UC Berkeley
California State University = Cal State L.A.

Thomas F Rosenbaum, Ph.D., *President; Sonja and William Davidow Presidential Chair; Professor of Physics*
A.B., Harvard College, 1977; M.A., Princeton University, 1979; Ph.D., 1982. Caltech, 2014-; President, 2014. Davidow Presidential Chair, 2014-.

. . . .

John N Abelson, Ph.D., *George Beadle Professor of Biology, Emeritus*
B.S., Washington State University, 1960; Ph.D., Johns Hopkins University, 1965. Professor, Caltech, 1982-91; Beadle Professor, 1991-2002; Beadle Professor Emeritus, 2002-. Chair, Division of Biology, 1989-95.

Yaser Abu-Mostafa, Ph.D., *Professor of Electrical Engineering and Computer Science*
B.Sc., Cairo University, 1979; M.S.E.E., Georgia Institute of Technology, 1981; Ph.D., Caltech, 1983. Garrett Research Fellow in Electrical Engineering, 1983; Assistant Professor, 1983-89; Associate Professor, 1989-94; Professor, 1994-.

Allan J Acosta, Ph.D., *Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, Emeritus*
B.S., Caltech, 1945; M.S., 1949; Ph.D., 1952. Assistant Professor, 1954-58; Associate Professor, 1958-66; Professor, 1966-90; Hayman Professor, 1990-93. Hayman Professor Emeritus, 1993-. Executive Officer for Mechanical Engineering, 1988-93.

Rana Adhikari, Ph.D., *Professor of Physics*
B.S., University of Florida (Gainesville), 1998; Ph.D., Massachusetts Institute of Technology, 2004. Assistant Professor, Caltech, 2006-12; Professor, 2012-.

Jess F Adkins, Ph.D., *Professor of Geochemistry and Global Environmental Science*
B.S., Haverford College, 1990; Ph.D., Massachusetts Institute of Technology, 1998. Assistant Professor, Caltech, 2000-06; Associate Professor, 2006-10; Professor, 2010-.

Ralph Adolphs, Ph.D., *Bren Professor of Psychology and Neuroscience and Professor of Biology*
B.S., Stanford University, 1986; M.S., 1986; Ph.D., Caltech, 1992. Professor of Psychology and Neuroscience, 2004-05; Bren Professor, 2005-; Professor of Biology, 2005-; Director, Caltech Brain Imaging Center, 2008-13.

Andreas Aebi, *Lecturer in German*
M.A., University of Southern California, 1970; Ph.D., 1974. Lecturer in French, Caltech, 1978; Lecturer in German, 1978-83; 1986-; Instructor in German, 1983-1986.

Theodor Agapie, Ph.D., *Professor of Chemistry*
B.S., Massachusetts Institute of Technology, 2001; Ph.D., Caltech, 2007. Assistant Professor, Caltech, 2009-14; Professor, 2014-.

Piyush S Agram, *Visiting Associate in Geophysics*
B.Tech., Indian Insitute of Technology of Madras, 2004; M.S., Standford University, 2006; Ph.D., 2010. Caltech, 2014-16.

Marina Agranov, Ph.D., *Assistant Professor of Economics*
B.A., St. Petersburg State Technical University, 1999; M.A., Tel Aviv University, 2004; Ph.D., New York University, 2010. Caltech, 2010-.

Oded Aharonson, *Visiting Associate in Planetary Science*
B.S., Cornell University, 1994; M.Eng., 1995; Ph.D., Massachusetts Institute of Technology, 2002. Assistant Professor, Caltech, 2002-08; Associate Professor, 2008-10; Professor, 2010-11. Visiting Associate, 2013-16.

David S Ahn, *Visiting Associate in Economics*
B.A., Emory University, 1999; Ph.D., Stanford University, 2004. Caltech, 2015.

Bader Al-Anzi, *Senior Research Fellow in Biology and Biological Engineering*
B.S., Kuwait University, M.S., Arizona State University, Ph.D., Yale University, 2003. Caltech, 2011-.

Arden L Albee, Ph.D., *Professor of Geology and Planetary Science, Emeritus*
A.B., Harvard College, 1950; A.M., Harvard University, 1951; Ph.D., 1957. Visiting Assistant Professor, Caltech, 1959-60; Associate Professor of Geology, 1960-66; Professor, 1966-99; Professor of Geology and Planetary Science, 1999-2002; Professor Emeritus, 2002-. Academic Officer, Geological and Planetary Sciences, 1971-79; Chief Scientist, Jet Propulsion Laboratory, 1979-84; Dean of Graduate Studies, 1984-2000.

Miguel Alcalde, *Visiting Associate in Chemical Engineering*
B.S., University of Madrid, 1993, Ph.D., 1999. Caltech, 2015.

Jason F Alicea, Ph.D., *Professor of Theoretical Physics*
B.S., University of Florida, 2001; M.A., University of California (Santa Barbara), 2005; Ph.D., 2007. Associate Professor, Caltech, 2012-15; Professor, 2015-.

Clarence R Allen, Ph.D., *Professor of Geology and Geophysics, Emeritus*
B.A., Reed College, 1949; M.S., Caltech, 1951; Ph.D., 1954. Assistant Professor, 1955-

59; Associate Professor, 1959-64; Professor, 1964-90; Professor Emeritus, 1990-. Interim Director, Seismological Laboratory, 1965-67; Acting Chairman, Division of Geology, 1967-68.

Mark Allen, *Visiting Associate in Planetary Science*
B.A., Columbia University, 1971; Ph.D., Caltech, 1976. Member of the Technical Staff, Jet Propulsion Laboratory, 1984-. Research Fellow, Caltech, 1978-81; Institute Visiting Associate, 1987-88; Visiting Associate, 1981-86; 1988-96; 2001-14; Faculty Associate, l996-2001.

John M Allman, Ph.D., *Frank P. Hixon Professor of Neurobiology*
B.A., University of Virginia, 1965; A.M., University of Chicago, 1968; Ph.D., 1971. Assistant Professor, Caltech, 1974-77; Associate Professor, 1977-84; Professor, 1984-89; Hixon Professor, 1989-.

Paolo Aluffi, *Visiting Associate in Mathematics*
M.S., University of Turin, 1983; Ph.D., Brown University, 1987. Professor, Florida State University, 2000-. Caltech, 2008-15.

R M Alvarez, Ph.D., *Professor of Political Science*
B.A., Carleton College, 1986; M.A., Duke University, 1990; Ph.D., 1992. Assistant Professor, Caltech, 1992-95; Associate Professor, 1995-2002; Professor, 2002-.

Brendan P Ames, *von Karman Instructor in Computing and Mathematical Sciences*
B.S., University of Guelph, 2005; M.S., 2007; Ph.D., University of Waterloo, 2011. Caltech, 2013-14.

Jean Paul (Pablo) Ampuero Saenz, Ph.D., *Assistant Professor of Seismology*
B.S., University of Paris, VII; 1997; M.S., 1998; Ph.D., 2002. Caltech, 2008-.

Akash Anand, *Visiting Associate in Computing and Mathematical Sciences*
M.S., Indian Institute of Technology, Kanpur, 2000; Ph.D., University of Minnesota, 2006. Caltech, 2015-16.

Ebbe S Andersen, *Visiting Associate in Computing and Mathematical Sciences*
B.S., Aarhus University, 2000; M.S., 2002; Ph.D., 2006. Caltech, 2013-14.

Richard A Andersen, Ph.D., James G. Boswell Professor of Neuroscience
B.S., University of California (Davis), 1973; Ph.D., University of California (San Francisco), 1979. Caltech, 1993-.

David J Anderson, Ph.D., *Seymour Benzer Professor of Biology; Investigator, Howard Hughes Medical Institute*
A.B., Harvard University, 1978; Ph.D., Rockefeller University, 1983. Assistant Professor, Caltech, 1986-92; Associate Professor, 1992-96; Professor, 1996-2004; Roger W. Sperry Professor, 2004-09; Benzer Professor, 2009-. Assistant Investigator, 1989-92; Associate Investigator, 1992-97; Investigator, 1997-.

Don L Anderson, Ph.D., *Eleanor and John R. McMillan Professor of Geophysics, Emeritus*
B.S., Rensselaer Polytechnic Institute, 1955; M.S., Caltech, 1958; Ph.D., 1962. Research Fellow, 1962-63; Assistant Professor, 1963-64; Associate Professor, 1964-68; Professor, 1968-89; McMillan Professor, 1989-2002; MacMillan Professor Emeritus, 2002-14. Director, Seismological Laboratory, 1967-89.

Jose E Andrade, Ph.D., *Professor of Civil and Mechanical Engineering*
B.S., Florida Institute of Technology, 2001; M.S., Stanford University, 2003; PhD, 2006. Assistant Professor, Caltech, 2010; Associate Professor, 2010-13; Professor, 2013-.

Lachlan L Andrew, *Visiting Associate in Computing and Mathematical Sciences*
B.S., University of Melbourne, 1992; B.Sc., 1993; Ph.D., 1997. Associate Professor, Swinburne University of Technology, 2008-. Caltech, 2008-16.

Fred C Anson, Ph.D.,*D.h.c., Elizabeth W. Gilloon Professor of Chemistry, Emeritus*
B.S., Caltech, 1954; Ph.D., Harvard University, 1957; D.h.c., University of Paris VII, 1993. Instructor, Caltech, 1957-58; Assistant Professor, 1958-62; Associate Professor, 1962-68; Professor, 1968-95; Gilloon Professor, 1995-2001; Gilloon Professor Emeritus 2001-. Executive Officer for Chemistry, 1973-77; Chairman, Division of Chemistry and Chemical Engineering, 1984-94.

Kristin Antelman, *University Librarian*
B.A., University of Michigan, 1982; M.A., Columbia University, 1985; M.A., The University of Chicago, 1988. Caltech, 2014-.

Dimitrios Antsos, *Lecturer in Electrical Engineering*
B.S., Caltech, 1990; M.S., 1991; Ph.D., 1994. Lecturer, 1994-99; 2004-10; 2012; 2013; 2014; 2015.

Tom M Apostol, Ph.D., *Professor of Mathematics, Emeritus*
B.S., University of Washington, 1944; M.S., 1946; Ph.D., University of California, 1948. Assistant Professor, Caltech, 1950-56; Associate Professor, 1956-62; Professor, 1962-92; Professor Emeritus, 1992-.

Koji Arai, *Research Assistant Professor of Experimental Physics*
Ph.D., University of Toyko, 2002. Caltech, 2009-15.

Alexei Aravin, Ph.D., *Assistant Professor of Biology*
B.S., University of Moscow, 1997; M.Sc., 1998; Ph.D., 2002. Caltech, 2009-.

Jasmina Arifovic, *Visiting Associate in Economics*
B.A., University of Sarajevo, 1981; M.A., University of Chicago, 1988; Ph.D., 1991. Professor, Simon Fraser University (Canada), 2002-. Visiting Associate Professor, Caltech, 1999-2001; Visiting Associate, 2002-15.

Gloria Arjona, *Lecturer in Spanish*
B.A., California State University, 1993; M.A., University of Southern California, 1997; Ph.D., 2002. Caltech, 2000-17.

Frances H Arnold, Ph.D., *D.h.c., Dick and Barbara Dickinson Professor of Chemical Engineering, Bioengineering and Biochemistry; Director, Donna and Benjamin M. Rosen Bioengineering Center*
B.S., Princeton University, 1979; Ph.D., University of California, 1985; D.h.c., Stockholm University. Visiting Associate, Caltech, 1986; Assistant Professor, 1987-92; Associate Professor, 1992-96; Professor, 1996-99; Professor of Chemical Engineering and Biochemistry, 1999-2000. Dickinson Professor, 2000-; Director, Rosen Bioengineering Center, 2013-.

Stephen Arnold, *Visiting Associate in Biology and Biological Engineering*
B.S., University of Toledo, 1964; Ph.D., City University. Caltech, 2014-.

Junichi Asama, *Visiting Associate in Mechanical and Civil Engineering*
B.S, Tokyo Institute of Technology, 2002; M.S., 2004; Ph.D., 2006. Caltech, 2013-15.

Yoshiharu Asaoka, *Visiting Associate in Chemical Engineering*
B.S., Mie University, 2003; M.S., 2005; Ph.D., 2013. Caltech, 2015-16.

Michael Aschbacher, Ph.D., *Shaler Arthur Hanisch Professor of Mathematics, Emeritus*
B.S., Caltech, 1966; Ph.D., University of Wisconsin, 1969. Bateman Research Instructor, Caltech, 1970-72; Assistant Professor, 1972-74; Associate Professor, 1974-76; Professor, 1976-96; Hanisch Professor, 1996-2013; Hanisch Professor, Emeritus, 2013-; Executive Officer for Mathematics, 1991-94.

Domniki Asimaki, Ph.D., *Professor of Mechanical and Civil Engineering Dipl., National Technical University of Athens, 1998;*
M.S., Massachusetts Institute of Technology, 2000; Ph.D., 2004. Caltech, 2014-.

Paul D Asimow, Ph.D., *Professor of Geology and Geochemistry*
A.B., Harvard University, 1991; M.S., Caltech, 1993; Ph.D., 1997. Assistant Professor, 1999-2005; Associate Professor, 2005-2010; Professor, 2010-.

Harry A Atwater, Ph.D., *Howard Hughes Professor of Applied Physics and Materials Science; Director, Joint Center for Artificial Photosynthesis*
B.S., Massachusetts Institute of Technology, 1982; M.S., 1983; Ph.D., 1987. Assistant Professor, Caltech, 1988-94; Associate Professor, 1994-99; Professor of Applied Physics and Materials Science, 1999-2002; Howard Hughes Professor, 2002-. Director of Resnick Sustainability Institute, 2009-15; Director of Joint Center for Artificial Photosynthesis, 2014-.

Joanna M Austin, Ph.D., *Professor of Aerospace*
B.E., University of Queensland, 1996; B.S., 1996; M.S., California Institute of Technology, 1998; Ph.D., 2003. Caltech, 2014-.

Jean-Philippe Avouac, Ph.D., *Earle C. Anthony Professor of Geology*
M.E., Ecole Polytechnique, 1987; Ph.D., Institut de Physique du Globe, 1991; Habil., 1992. Professor, Caltech, 2003-11; Anthony Professor, 2012-; Director, Tectonic Observatory, 2004-13.

Tari Awipi, *Lecturer in Psychology*
B. A., New York University, 2001; Ph.D., 2009. Caltech, 2015.

Mokhles K Azer, *Visiting Associate in Geology*
B.S., Assiut University, 1994; M.S., Cairo University, 2000; Ph.D, 2004. Caltech, 2015.

Shinpei Baba, *Olga Taussky and John Todd Instructor in Mathematics*
M.S., Kyoto University; Ph.D., University of California (Davis), 2009. Caltech, 2011-14.

John D Baker, *Lecturer in Aerospace*
B.S., Colorado State University, 1986. Caltech, 2013; 2015.

Mark J Balas, *Visiting Associate in Computing and Mathematical Sciences*
B.S., University of Akron; M.S., University of Maryland, 1970; M.S., University of Denver, 1974; Ph.d, 1974. Caltech, 2011-14.

John D Baldeschwieler, Ph.D., *J. Stanley Johnson Professor and Professor of Chemistry, Emeritus B.Chem.E., Cornell University, 1956;*
Ph.D., University of California, 1959. Professor, Caltech, 1973-96; Johnson Professor and Professor of Chemistry, 1996-99; Johnson Professor and Professor Emeritus, 1999-. Chairman, Division of Chemistry and Chemical Engineering, 1973-78.

David Baltimore, Ph.D., *D.Sc.h.c., D.Phil.h.c., Nobel Laureate., President Emeritus; Robert Andrews Millikan Professor of Biology*
B.A., Swarthmore College, 1960; Ph.D., Rockefeller University, 1964; D.Sc.h.c., Swarthmore College; Mount Holyoke College; Mount Sinai Medical Center; Bard College; University of Helsinki; Cold Spring Harbor Laboratory; University of Alabama; California Polytechnic State University; Columbia University; Yale University;

Rockefeller University; Harvard University; D.Phil.h.c., Weizmann Institute of Science. Professor, Caltech, 1997-2006; Millikan Professor, 2006-. President, 1997-2006, President Emeritus, 2006-.

Jie Bao, *Visiting Associate in Physics*
B.S., Tsinghua University, 2006; Ph.D., Brown University, 2010. Caltech, 2014-16.

Yuequan Bao, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Harbin Institute of Technology, 2003; M.S., 2005; Ph.D., 2009. Caltech, 2014-15.

Susan J Barbour, *Visiting Associate in the Humanities*
B.A., Dartmouth College, 2000; M.A., Johns Hopkins University, 2002; Ph.D., University of Oxford, 2014. Caltech, 2014-15.

Barry C Barish, Ph.D., *Laurea h.c., Ronald and Maxine Linde Professor of Physics, Emeritus*
B.A., University of California, 1957; Ph.D., 1962; Laurea, h.c., University of Bologna. Research Fellow, Caltech, 1963-66; Assistant Professor, 1966-69; Associate Professor, 1969-72; Professor, 1972-91; Linde Professor, 1991-2005; Linde Professor Emeritus, 2005-. Principal Investigator of LIGO, 1994-97; Director, LIGO, 1997-2006.

Alan H (Al) Barr, *Ph.D., Professor of Computer Science*
B.S., Rensselaer Polytechnic Institute, 1973; M.S., 1976; Ph.D., 1983. Research Fellow, Caltech, 1984; Assistant Professor, 1984-90; Associate Professor, 1990-98; Professor, 1998-; Executive Officer for Computer Science, 2000-01.

Jim Barry, *Lecturer in Art-Drawing, Painting, Silkscreen, and Airbrush*
B.A., University of California (Santa Barbara), 1972. Caltech, 1999-2015.

Jacqueline K Barton, Ph.D., *D.Sc.h.c., D.L.h.c., Arthur and Marian Hanisch Memorial Professor of Chemistry; Chair, Division of Chemistry and Chemical Engineering*
A.B., Barnard College, 1974; Ph.D., Columbia University, 1978; D.Sc.h.c., New Jersey Institute; Kenyon College; Yale University; Hamilton College; Williams College; Lawrence University; Columbia University; D.L.h.c., Skidmore College. Visiting Associate, Caltech, 1989; Professor, 1989-; Hanisch Professor, 1997-. Division Chair, 2009-.

Konstantin Batygin, Ph.D., *Assistant Professor of Planetary Science*
B.S., UC Santa Cruz, 2008; M.S., California Institute of Technology, 2010; Ph.D., 2012. Caltech, 2014-.

Elaine L Bearer, *Visiting Associate in Biology B.M., Manhattan School of Music, 1970;*
M.A., New York University, 1973; M.D., University of California (San Francisco), 1983; Ph.D., 1983. Professor, Brown University, 2004-. Visiting Associate in Biology, Caltech, 2004; 2005-15; Moore Distinguished Scholar, 2004-05.

Jesse L (Jack) Beauchamp, Ph.D., *Mary and Charles Ferkel Professor of Chemistry*
B.S., Caltech, 1964; Ph.D., Harvard University, 1967. Noyes Research Instructor, Caltech, 1967-69; Assistant Professor, 1969-71; Associate Professor, 1971-74; Professor, 1974-2000; Ferkel Professor, 2000-.

James L (Jim) Beck, Ph.D., *George W. Housner Professor of Engineering and Applied Science*
B.Sc., University of Auckland, 1969; M.Sc., 1970; Ph.D., Caltech, 1979. Assistant Professor of Civil Engineering, 1981-87; Associate Professor, 1987-96; Professor, 1996-2011; Housner Professor, 2012-; Executive Officer for Applied Mechanics and Civil Engineering, 1993-98.

Fahmi Bedoui, *Visiting Associate in Chemistry*
B.S., ENSIM Mulhouse, 2001; M.Sc, ENS Cachan, 2002; Ph.D, ENSAM Paris Tech, 2005. Caltech, 2015.

Josette Bellan, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Lycee Jules Ferry, 1964; M.S., University of Sciences (Paris), 1969; M.S., Princeton University, 1972; Ph.D., 1974. Senior Research Scientist, Jet Propulsion Laboratory, 1997-. Lecturer in Jet Propulsion, Caltech, 1992-93; Visiting Associate in Aeronautics, 1995-2006; Visiting Associate in Mechanical and Civil Engineering, 2006-15.

Paul M Bellan, Ph.D., *Professor of Applied Physics*
B.Sc., University of Manitoba, 1970; M.A., Princeton University, 1972; Ph.D., 1976. Assistant Professor, Caltech, 1977-83; Associate Professor, 1983-89; Professor, 1990-.

Andrea P Belz, *Visiting Professor in Engineering*
B.S., University of Maryland, 1993; Ph.D., California Institute of Technology, 1999. Caltech, 2002; 2015.

Shelley M Bennett, *Lecturer in Art History*
B.A., University of California (Riverside), 1969; M.A., University of California (Los Angeles), 1975; Ph.D., 1977. Caltech, 1986-2014.

John E Bercaw, Ph.D., *Centennial Professor of Chemistry, Emeritus*
B.S., North Carolina State University, 1967; Ph.D., University of Michigan, 1971. Arthur Amos Noyes Research Fellow, Caltech, 1972-74; Assistant Professor, 1974-77; Associate

Professor, 1977-79; Professor, 1979-93; Shell Distinguished Professor, 1985-90; Centennial Professor, 1993-15; Centennial Professor, Emeritus, 2015-. Executive Officer for Chemistry, 1999-2002.

Zvi Bern, Ph.D., *Moore Distinguished Scholar*
B.S., Massachusetts Institute of Technology, 1982; Ph.D., University of California, Berkeley, 1986. Caltech, 2015.

Marco Bernardi, Ph.D., *Assistant Professor of Applied Physics and Materials Science*
B.S., University of Rome La Sapienza, 2004; M.S., University of Rome Tor Vergata, 2008; Ph.D., Massachusetts Institute of Technology, 2013. Assistant Professor, Caltech, 2015-.

Joseph Bernstein, *Visiting Associate in Mathematics*
Ph.D., Moscow State University, 1972. Caltech, 2014.

L E (Elizabeth) Bertani, *Lecturer in Biology*
B.S., University of Michigan, 1953; Ph.D., Caltech, 1957. Retired, Karolinska Institute (Stockholm), 1981-. Visiting Associate in Biology and Chemistry, Caltech, 1981-85; Lecturer in Biology, 1993-94; 1994-95; 1996; 1997-98; 1998-99 2012; 2013; 2014; Visiting Associate in Biology, 1995-1999.

Emanuele Berti, *Visiting Associate in Physics*
Ph.D., University of Rome, 2002. Caltech, 2010-16.

Kaushik Bhattacharya, Ph.D., *Howell N. Tyson, Sr., Professor of Mechanics and Professor of Materials Science; Executive Officer for Mechanical and Civil Engineering*
B.Tech., Indian Institute of Technology, 1986; Ph.D., University of Minnesota, 1991. Assistant Professor, Caltech, 1993-99; Associate Professor, 1999-2000; Professor, 2000-10; Tyson, Sr., Professor, 2010-; Executive Officer, 2007-.

Kathryn Bikle, *Lecturer in Chemistry*
B.A., University of California (Santa Cruz), 1981; M.A., University of California, 1984. Lecturer in Chemistry, Caltech, 2000-14; Lecturer in Geology, 2000-14; 2015.

Igor A Bilenko, *Visiting Associate in Physics*
Ph.D., Moscow State University, 1991. Associate Professor, 1999-. Caltech, 2005-10; 2013; 2014-17.

Joseph G Billock, *Lecturer in Computing and Mathematical Sciences*
B.S., Walla Walla College, 1994; M.S., California Institute of Technology, 1995; Ph.D., 2001. Caltech, 2012; 2013; 2014; 2015.

Delores M Bing, *Lecturer in Chamber Music*
B.M., Drake University, 1970; M.M., University of Southern California, 1972. Lecturer, Coordinator, 2007-11. Lecturer in Chamber Music, Caltech, 1999-.
William W (Bill) Bing, *Lecturer in Concert Band and Jazz Band*
B.M., University of Michigan, 1965; M.M., University of Southern California, 1971. Caltech, 2000-.

Pamela J Bjorkman, Ph.D., *Centennial Professor of Biology*
B.A., University of Oregon, 1978; Ph.D., Harvard University, 1984. Assistant Professor, Caltech, 1989-95; Associate Professor, 1995-98; Professor, 1998-2004; Delbruck Professor, 2004-2015; Centennial Professor, 2015-. Assistant Investigator, 1989-95; Associate Investigator, 1995-98; Investigator, 1998-2000; 2005-2015. Full Investigator, 2000-05. Executive Officer for Biology, 2000-06.

Eric Black, *Lecturer in Physics*
B.S., University of Tennessee, 1991; M.S., University of Colorado, 1994; Ph.D., 1996. Caltech, 2001-15.

Geoffrey A (Geoff) Blake, Ph.D., *Professor of Cosmochemistry and Planetary Sciences and Professor of Chemistry*
B.S., Duke University, 1981; Ph.D., Caltech, 1986. Assistant Professor of Cosmochemistry, 1987-93; Associate Professor of Cosmochemistry and Planetary Sciences, 1993-97; Professor, 1997-99; Professor of Cosmochemistry and Planetary Sciences and Professor of Chemistry, 1999-. Deputy Director, Owens Valley Radio Observatory, 2000-06; Master of Student Houses, 2009-14.

Guillaume Blanquart, Ph.D., *Professor of Mechanical Engineering*
B.S., M.S., Ecole Polytechnique, 2002; M.S., Stanford University, 2004; Ph.D., 2008; Assistant Professor, Caltech, 2009-15; Professor, 2015-.

Jonathan David Blundy, Ph.D., *Moore Distinguished Scholar in Geology*
B.A., University of Oxford, 1983; Ph.D., University of Cambridge, 1989; Moore Distinguished Scholar, Caltech, 2014.

James J (Jamie) Bock, Ph.D., *Professor of Physics; Jet Propulsion Laboratory Senior Research Scientist*
B.S., Duke University, 1987; M.A., University of California, Berkeley, 1990; Ph.D., 1994. Jet Propulsion Laboratory Research Scientist, 1994-2012; Visiting Associate, Caltech, 1994-2008; Senior Faculty Associate, 2008-12; Professor, 2012-; Jet Propulsion Laboratory Senior Research Scientist, 2012-.
Marc W Bockrath, Visiting Associate in Applied Physics B.S., Massachusetts Institute of Technology, 1993; Ph.D., University of California, 1999. Visiting Associate, Caltech, 2002; 2009-14; Assistant Professor, 2002-09.

Daniel J Bodony, *Visiting Professor of Mechanical and Civil Engineering*
B.S., Purdue University, West Lafayette, 1997; M.S., 1999; Ph.D., Stanford University, 2005. Caltech, 2015.
Felix H Boehm, Ph.D., *William L. Valentine*

Professor of Physics, Emeritus Dipl., Federal Institute of Technology (Zurich), 1948;
Ph.D., 1951. Research Fellow, Caltech, 1953-55; Senior Research Fellow, 1955-58; Assistant Professor, 1958-59; Associate Professor, 1959-61; Professor, 1961-85; Valentine Professor, 1985-95; Valentine Professor Emeritus, 1995-.

Carmen Boening, *Visiting Associate in Environmental Science and Engineering*
M.S., University of Bremen, 2005; Ph.D., 2009. Caltech, 2013-15.

Justin S Bois, *Lecturer in Biology and Biological Engineering*
B.S., University of Illinois (Urbana-Champaign), 1999; Ph.D., Caltech, 2007. Caltech, 2014-17.

Ian R Booth, *Visiting Associate in Chemistry*
B.S., University of Liverpool, 1972; Ph.D., University College of Wales, 1975. Caltech, 2012, 2013-15.

Kim C Border, Ph.D., *Professor of Economics*
B.S., Caltech, 1974; Ph.D., University of Minnesota, 1979. Assistant Professor, Caltech, 1979-83; Associate Professor, 1983-95; Professor, 1995-. Executive Officer for the Social Sciences, 1995-99.

Simona Bordoni, Ph.D., *Assistant Professor of Environmental Science and Engineering Dipl., University of Rome Tor Vergata, 1996;*
M.S., University of California (Los Angeles), 2003; Ph.D., 2007. Moore Postdoctoral Fellow, Caltech, 2007; Assistant Professor, 2009-.

Peter L Bossaerts, *Visiting Associate in Finance Doctorandus, Universitaire Faculteiten Sint Ignatius (Belgium), 1982;*
Ph.D., University of California (Los Angeles), 1986. Assistant Professor of Finance, Caltech, 1990-94; Associate Professor, 1994-98; Professor, 1998-2013; Hacker Professor, 2003-2013. Executive Officer for the Social Sciences, 2002-05; Chair, Division of the Humanities and Social Sciences, 2006-07. Visiting Associate in Finance, 2013-.

Sven C Bossuyt, *Visiting Associate in Applied Physics and Materials Science*
M.S, California Institute of Technology, 1997; Ph.D., 2001. Caltech, 2013-14; 2015.

Charles M (Matt) Bradford, *Visiting Associate in Physics*
B.S., Stanford University, 1994; Ph.D., Cornell University, 2001. Research Scientist, Jet Propulsion Laboratory, 2003-. Caltech, 2004-16.

Samuel C Bradford, *Visiting Associate in Aerospace*
B.S., Rice University, 2005; M.S., University of California, Berkeley, 2006; Ph.D., California Institute of Technology, 2006. Caltech, 2013-18.

John F Brady, Ph.D., *Chevron Professor of Chemical Engineering and Mechanical Engineering; Executive Officer for Chemical Engineering*
B.S., University of Pennsylvania, 1975; M.S., Stanford University, 1977; Ph.D., 1981. Associate Professor, Caltech, 1985-89; Professor, 1990-99; Chevron Professor, 1999-; Professor of Mechanical Engineering, 2005-. Executive Officer for Chemical Engineering, 1993-99; 2013-.

Robert D (Bobby) Braun, Ph.D., *Moore Distinguished Scholar in Aerospace*
B.S., Pennsylvania State University, 1987; M.S., George Washington University, 1989; Ph.D., Stanford University, 1996. Caltech, 2015.

James B (Jim) Breckinridge, *Visiting Associate in Aerospace*
B.Sc., Case Institute of Technology, 1961; M.Sc., University of Arizona, 1970; Ph.D., 1976. Lecturer in Applied Physics, Caltech, 1982; 1984-1991; 1993-96; 1998; Lecturer in Aeronautics, 2007, 2008, 2009, 2012, 2014; Visiting Associate, 2009-15.

Louis Breger, Ph.D., *Professor of Psychoanalytic Studies, Emeritus*
B.A., University of California (Los Angeles), 1957; M.A., Ohio State University, 1959; Ph.D., 1961. Visiting Associate Professor of Psychology, Caltech, 1970-71; Associate Professor, 1971-80; Associate Professor of Psychology and the Humanities, 1980-83; Professor of Psychoanalytic Studies, 1983-94; Professor Emeritus, 1994-.

Lindsay R Bremner, *Lecturer in Biology and Biological Engineering*
B.A., St. Catherines College, 2000; Ph.D., University College Longdon, 2007. Caltech, 2013-.

Christopher E Brennen, D.Phil., *Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, Emeritus*
B.A., University of Oxford, 1963; M.A., D.Phil., 1966. Research Fellow, Caltech, 1969-72; Senior Research Fellow, 1972-75; Research Associate, 1975-76; Associate Professor, 1976-82; Professor, 1982-2005; Hayman Professor, 2005-10; Hayman Professor, Emeritus, 2010-. Master of Student Houses, 1983-87; Dean of Students, 1988-92; Executive Officer for Mechanical Engineering, 1993-97; Vice President for Student Affairs, 1997-2002.

John Brewer, Ph.D., *Eli and Edye Broad Professor of Humanities and Social Sciences; Professor of History and Literature*
B.A., University of Cambridge, 1968; M.A., 1972; Ph.D., 1973; M.A. Honorary Degree, Harvard University. Moore Distinguished Scholar, Caltech, 2001; Professor, 2002-; Broad Professor, 2003-.

William B Bridges, Ph.D., *Carl F Braun Professor of Engineering, Emeritus*
B.S., University of California, 1956; M.S., 1957; Ph.D., 1962. Sherman Fairchild Distinguished Scholar, Caltech, 1974-75; Professor of Electrical Engineering and Applied Physics, 1977-83; Braun Professor, 1983-2002; Braun Professor Emeritus, 2002-. Executive Officer for Electrical Engineering, 1978-81.

Jeandrew Brink, *Visiting Associate in Physics*
B.Sc., University of the Free State, 1998; B.Sc, 1999; M.A., 2000; Ph.D., Carnell University, 2005. Caltech, 2010-14.

Roland Brockers, *Lecturer in Mechanical and Civil Engineering*
Dipl-FH, Niederrhein University of Applied Science, 1993; Dipl., University of Paderborn (Germany), 1999; Ph.D., 2005. Caltech, 2012, 2013, 2015.

Charles J Brokaw, Ph.D., *Professor of Biology, Emeritus*
B.S., Caltech, 1955; Ph.D., University of Cambridge, 1958. Visiting Assistant Professor, Caltech, 1960; Assistant Professor, 1961-63; Associate Professor, 1963-68; Professor, 1968-2000; Professor Emeritus, 2000-. Executive Officer for Biology, 1976-80; 1985-89; Associate Chairman of the Division of Biology, 1980-85.

Marianne Bronner Hansen, Ph.D., *Albert Billings Ruddock Professor of Biology; Executive Officer for Neurobiology*
Sc.B., Brown University, 1975; Ph.D., Johns Hopkins University, 1979. Professor, Caltech, 1996-2000; Ruddock Professor, 2000-; Executive Officer, 2013-.

Norman H Brooks, Ph.D., *James Irvine Professor of Environmental and Civil Engineering, Emeritus*
A.B., Harvard College, 1949; M.S., Harvard University, 1950; Ph.D., Caltech, 1954. Instructor in Civil Engineering, 1953-54; Assistant Professor, 1954-58; Associate Professor, 1958-62; Professor, 1962-70; Professor of Environmental Science and Civil Engineering, 1970-76; Irvine Professor of Environmental Engineering Science, 1976-77; Irvine Professor of Environmental Engineering and Civil Engineering 1977-95; Irvine Professor Emeritus, 1995-. Academic Officer for Environmental Engineering Science, 1972-74; Director, Environmental Quality Laboratory, 1974-93; Executive Officer for Environmental Engineering Science, 1985-93.

Brian Brophy, *Lecturer in Theater-Performing and Creative Arts*
B.S., Montana State University, 1981; M.A., California State University (Los Angeles), 1999; M.F.A., University of California (Riverside), 2006. Caltech, 2009-15.

Michael E (Mike) Brown, Ph.D., *Richard and Barbara Rosenberg Professor and Professor of Planetary Astronomy*
A.B., Princeton University, 1987; M.A., University of California, 1990; Ph.D., 1994. Visiting Associate, Caltech, 1995; Assistant Professor, 1997-2002; Associate Professor, 2002-04; Professor, 2005-2008; Rosenberg Professor, 2008-.

Warren C Brown, Ph.D., *Professor of History B.S., Tufts University, 1985;*
M.A., University of Cincinnati, 1993; Ph.D., University of California (Los Angeles), 1997. Assistant Professor, Caltech 1997-2003; Associate Professor, 2003-10; Professor, 2010-.

Jehoshua (Shuki) Bruck, Ph.D., *Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering*
B.Sc., Technion-Israel Institute of Technology, 1982; M.Sc., 1985; Ph.D., Stanford University, 1989. Associate Professor, Caltech, 1994-98; Professor, 1998-2001; Moore Professor, 2001-. Director, Information Science and Technology, 2003-05.

Todd Brun, *Visiting Associate in Theoretical Physics*
Ph.D., Caltech, 1994. Professor, University of Southern California, 2003-. Caltech, 2007-15.

Oscar P Bruno, Ph.D., *Professor of Applied and Computational Mathematics*
Lic., University of Buenos Aires, 1982; Ph.D., New York University (Courant Institute of Mathematical Sciences), 1989. Associate Professor, Caltech, 1995-98; Professor, 1998-. Executive Officer for Applied Mathematics, 1998-2000.

Jed Z Buchwald, Ph.D., *Doris and Henry Dreyfuss Professor of History*
B.A., Princeton University, 1971; M.A., Harvard University, 1973; Ph.D., 1974. Caltech, 2001-.

Joel W Burdick, Ph.D., *Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering; Jet Propulsion Laboratory Research Scientist*
B.S., Duke University, 1981; M.S., Stanford University, 1982; Ph.D., 1988. Assistant Professor, Caltech, 1988-94; Associate Professor, 1994-2000; Professor of Mechanical Engineering, 2000-02; Professor of Mechanical Engineering and Bioengineering, 2002-12; Executive Officer for ioengineering, 2006-07; Hayman Professor, 2012-; Jet Propulsion Laboratory Research Scientist, 2014-.

Donald S Burnett, Ph.D., *Professor of Nuclear Geochemistry, Emeritus*
B.S., University of Chicago, 1959; Ph.D., University of California, 1963. Research

Fellow in Physics, Caltech, 1963-65; Assistant Professor of Nuclear Geochemistry, 1965-68; Associate Professor, 1968-75; Professor, 1975-2006; Professor Emeritus, 2006-. Academic Officer, Division of Geological and Planetary Sciences, 1979-87.

Long Cai, Ph.D., *Assistant Professor of Chemistry*
B.A, Harvard University, 2001; Ph.D., 2006. Caltech, 2010-.

Colin F Camerer, Ph.D., *Robert Kirby Professor of Behavioral Economics*
B.A., Johns Hopkins University, 1976; M.B.A., University of Chicago, 1979; Ph.D., 1981. Visiting Associate, Caltech, 1993; Rea A. and Lela G. Axline Professor of Business Economics, 1994-2008; Kirby Professor of Behavioral Finance and Economics, 2008; Kirby Professor, 2008-.

Robert A (Andy) Cameron, *Senior Research Associate in Biology, Emeritus*
B.A., San Jose State College, 1968; Ph.D., University of California (Santa Cruz), 1975. Visiting Associate, Caltech, 1984-85; Senior Research Fellow, 1985-89; Senior Research Associate, 1989-2015; Senior Research Associate, Emeritus, 2015-.

Judith L Campbell, Ph.D., *Professor of Chemistry and Biology*
B.A., Wellesley College, 1965; Ph.D., Harvard University, 1974. Assistant Professor of Chemistry, Caltech, 1977-83; Associate Professor, 1983-85; Associate Professor of Chemistry and Biology, 1985-89; Professor, 1989-.

Stijn Cassenaer, *Broad Senior Research Fellow in Biology*
B.S., University of California (San Diego), 1999; Ph.D., Caltech, 2007. Senior Research Fellow, 2009-.

Kylie R Catchpole, *Visiting Associate in Applied Physics and Materials Science*
B.S., Austalian National University, 1996; Ph.D., 2001. Caltech, 2015.

Martin V Chalifour, *Visiting Associate in the Humanities*
B.M., Curtis Institute, 1984. Caltech, 2013-15.

Jean-Lou A Chameau, Ph.D., *D.Sc.h.c., President Emeritus Ing., Ecole Nationale Superieure D'Arts et Metiers, 1976;*
M.S., Stanford University, 1977; Ph.D., 1981; D.Sc.h.c., Occidental College. Professor of Civil Engineering, Environmental Science and Engineering, and Mechanical Engineering, 2006-13; Davidow Presidential Professor, 2013; President, 2006-13; President Emeritus, 2013-.

David C Chan, Ph.D., *Professor of Biology A.B., Harvard College, 1988;*
M.D., Harvard Medical School, 1996; Ph.D., 1996. Assistant Professor, Caltech, 2000-06; Bren Scholar, 2000-06; Associate Professor, 2006-10; Professor, 2010-; Howard Hughes Medical Institute Investigator, 2008-2014.

Garnet K Chan, Ph.D., *Moore Distinguished Scholar*
B.A., Christ's College, University of Cambridge, 1996; M.A., Ph.D., 2000. Caltech, 2014, 2015.

Sunney I Chan, Ph.D., *George Grant Hoag Professor of Biophysical Chemistry, Emeritus*
B.S., University of California, 1957; Ph.D., 1961. Assistant Professor of Chemical Physics, Caltech, 1963-64; Associate Professor, 1964-68; Professor, 1968-76; Professor of Chemical Physics and Biophysical Chemistry, 1976-92; Hoag Professor, 1992-2001; Hoag Professor Emeritus, 2002-. Acting Executive Officer for Chemistry, 1977-78; Executive Officer, 1978-80; 1989-94; Master of Student Houses, 1980-83.

Venkat Chandrasekaran, Ph.D., *Assistant Professor of Computing and Mathematical Sciences and Electrical Engineering*
B.A., Rice University, 2005; B.S., 2005; M.S., Massachusetts Institute of Technology, 2007; Ph.D., 2011. Caltech, 2012-.

Kanianthra M (Mani) Chandy, Ph.D., *Simon Ramo Professor of Computer Science, Emeritus*
B.Tech., Indian Institute of Technology, 1965; M.S., Polytechnic Institute of Brooklyn, 1966; Ph.D., Massachusetts Institute of Technology, 1969. Sherman Fairchild Distinguished Scholar, Caltech, 1988; Visiting Professor, 1988-89; Professor, 1989-; Ramo Professor, 1997-2014; Ramo Professor, Emeritus, 2014-. Executive Officer for Computer Science, 1997-2000; Deputy Chair, 2009-12.

Se Myong (Sam) Chang, *Visiting Associate in Aerospace*
Ph.D., Korea Advanced Institute of Science and Technology, 2000. Caltech, 2014-15. Goutam Chattopadhyay, Visiting Associate in Physics Ph.D., Caltech, 1999. Senior Member of the Engineering Staff, Jet Propulsion Laboratory, 2005-. Visiting Associate, Caltech, 2006-16.

Shaoping Chen, *Visiting Associate in Applied Physics and Materials Science*
B.S., Taiyan University of Technology, 2000; M.S., 2003; Ph.D., 2010. Caltech, 2014-15.

Xie Chen, Ph.D., *Assistant Professor of Theoretical Physics*
B.S., Tsinghua University China, 2006; Ph.D., Massachusetts Institute of Technology, 2012. Caltech, 2014-.

Yanbei Chen, Ph.D., *Professor of Physics*
B.S., Peking University, 1999; Ph.D., Caltech, 2003. Visiting Associate, Caltech, 2005-07; Assistant Professor, 2007-10; Associate Professor, 2010-13; Professor, 2013-.

Robert Chess, *Lecturer in Engineering*
B.S., California Institute of Technology, 1978; M.B.A., Harvard University, 1980. Caltech, 2014; 2015.

Clifford W Cheung, Ph.D., *Assistant Professor of Theoretical Physics*
B.S., Yale University, 2004; M.A., Harvard University, 2006; Ph.D., 2009. Caltech, 2012-.

Vikram S Chib, *Visiting Associate in Neuroscience*
B.S., University of Pittsburgh, 2001; M.S., Northwestern University, 2003; Ph.D., 2007. Caltech, 2014-16.

Karsten O Chipeniuk, *Harry Bateman Research Instructor in Mathematics*
B.S., University of Victoria, 2005; M.S., University of British Columbia, 2007; Ph.D., 2011. Caltech, 2013-14.

Calum R Chisholm, *Visiting Associate in Applied Physics and Materials Science*
B.S., Yale University, 1995; M.S., Caltech, 2000; Ph.D., 2003. Vice President, SuperProtonic, Inc., 2005-. Caltech, 2008-14.

Young Dahl Cho, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Seoul National University, 1995; M.S., 1997; Ph.D., 2002. Caltech, 2015-16.

Anne Chomyn, *Senior Research Associate in Biology, Emeritus*
B.S., Drexel University, 1972; Ph.D., Caltech, 1978. Research Fellow, 1978-82; Senior Research Fellow, 1982-87; Senior Research Associate, 1989-2007; Senior Research Associate Emeritus, 2007-; Lecturer in Biology, 2007.

Hyuck Choo, Ph.D., *Assistant Professor of Electrical Engineering*
B.S., Cornell University, 1996; M.S., 1998; Ph.D., University of California, Berkeley, 2007. Caltech 2011-.

Wongee Chun, *Visiting Associate in Environmental Science and Engineering*
B.S., Hanyang University, 1981; M.S., University of Utah, 1984; Ph.D., 1986. Caltech, 2010-15.

Ara Chutjian, *Visiting Associate in Chemistry*
B.S., Brown University, 1962; Ph.D., University of California, 1966. Senior Research Scientist, Jet Propulsion Laboratory, 1990-. Caltech, 1998-2016.

Fred Claire, *Lecturer in Social Sciences*
B.A., San Jose State, 1957. Caltech, 2013.

Robert W Clayton, Ph.D., *Professor of Geophysics; Divisional Academic Officer for Geological and Planetary Sciences*
B.A.Sc., University of Toronto, 1973; M.Sc., University of British Columbia, 1976; Ph.D., Stanford University, 1981. Assistant Professor of Exploration Geophysics, Caltech, 1981-85; Associate Professor, 1985-89; Professor of Geophysics, 1989-. Executive Officer for Geophysics, 1987-94; Acting Director, Seismological Laboratory, 1989; 2008-09; Deputy Director, 1989-90; Academic Officer, 2008-.

William M (Bil) Clemons, Ph.D., *Professor of Biochemistry*
B.S., Virginia Polytechnic Institute and State University, 1995; Ph.D., University of Utah, 2000. Assistant Professor of Chemistry, Caltech, 2005-07; Assistant Professor of Biochemistry, 2007-13; Professor, 2013-.

Rodney J Clifton, *Clark. B. Millikan Visiting Professor of Aerospace*
B.S., University of Nevraska, 1959; M.S., Carnegie Institute of Technolgy, 1961; Ph.D., 1964. Professor, Brown University, 1965-. Caltech, 2013; 2014; 2015.

John A Clithero, *Visiting Associate in Neuroeconomics*
B.A., Pomona College, 2005; M.A., Duke University, 2007; Ph.D., 2011. Caltech, 2014-16.

Elizabeth S Cochran, *Visiting Associate in Geophysics*
B.S., University of California, Santa Barbara, 2000; M.S., University of California, Los Angeles, 2003; Ph.D., 2005. Caltech, 2011-15.

Bruce N Cohen, *Lecturer in Biology*
B.A., Brandeis University, 1975; Ph.D., State University of New York (Albany), 1985. Research Fellow, Caltech, 1989-94; Visiting Associate, 2001-02; Lecturer, 2003; 2014.

Donald S (Don) Cohen, Ph.D., *Charles Lee Powell Professor of Applied Mathematics, Emeritus*
Sc.B., Brown University, 1956; M.S., Cornell University, 1959; Ph.D., New York University (Courant Institute), 1962. Assistant Professor of Mathematics, Caltech, 1965-67; Associate Professor of Applied Mathematics, 1967-71; Professor, 1971-98; Powell Professor, 1998-2003; Powell Professor Emeritus, 2003-. Executive Officer for Applied Mathematics, 1988-93; Chairman, Division of Engineering and Applied Science, 1990.

Judith G Cohen, Ph.D., *Kate Van Nuys Page Professor of Astronomy*
B.A., Radcliffe College, 1967; M.S., Caltech, 1969; Ph.D., 1971; B.S., University

of Arizona, 1978. Associate Professor, Caltech, 1979-88; Professor, 1988-2005; Page Professor, 2005-. Executive Officer for Astronomy, 1995-96.

Marshall H Cohen, Ph.D., *Professor of Astronomy, Emeritus*
B.E.E., Ohio State University, 1948; M.S., 1949; Ph.D., 1952. Visiting Associate Professor, Caltech, 1965; Professor of Radio Astronomy, 1968-90; Professor of Astronomy, 1990-95; Professor Emeritus, 1995-. Executive Officer for Astronomy, 1981-85.

Max L Coleman, *Visiting Associate in Chemistry*
B.Sc., University of London: 1966, M.Sc., University of Leeds, 1967; Ph.D., 1970. Caltech, 2013-17.

Andres Collazo, *Visiting Associate in Biology and Biological Engineering; Lecturer in Biology and Biological Engineering*
B.S., Cornell University, 1985; Ph.D., University of California, 1990. Scientist II, Section Chief, House Ear Institute, 2000-. Research Fellow, Caltech, 1991-94; Senior Research Fellow, 1994-96; Visiting Associate, 2005-10.

Michael J Collins, *Visiting Associate in Mathematics*
B.A., University of Oxford (St. John's College), 1965; M.A., University of Oxford (Christ Church), 1969; D.Phil., 1969. Fellow and Praelector, University of Oxford (University College), 1970-. Visiting Professor, Caltech, 1990-91; Visiting Associate, 2004; 2005; 2010; 2011; 2012; 2013; 2014.

Tim Colonius, Ph.D., *Professor of Mechanical Engineering*
B.S., University of Michigan (Ann Arbor), 1987; M.S., Stanford University, 1988; Ph.D., 1994. Assistant Professor, Caltech, 1994-2000; Associate Professor, 2000-05; Professor, 2005-.

Agustin J (AJ) Colussi, *Visiting Associate in Environmental Science and Engineering Lic., University of Buenos Aires, 1968;*
Ph.D., 1972. Visiting Associate, Caltech 1997-98; Senior Research Fellow, 1998-2004; Senior Research Associate, 2004-12; Visiting Associate, 2012-16.

Robert D (Dale) Conner, *Visiting Associate in Applied Physics and Materials Science*
B.S., California State Polytechnic University, 1989; M.S., Caltech, 1994; Ph.D., 1998. Assistant Professor, California State University (Northridge), 2006-. Visiting Associate, Caltech, 2001-02; Lecturer, 2002-04; Senior Research Fellow, 2003-06; Visiting Associate, 2006-15.

Asantha Cooray, *Visiting Associate in Physics*
B.S., Massachusetts Institute of Technology, 1997; M.S., 1997; M.S., University of Chicago, 1998; Ph.D., 2001. Assistant Professor, University of California (Irvine), 2005-. Sherman Fairchild Senior Research Fellow, Caltech, 2001-05; Visiting Associate, 2005-15.

Jernej Copic, *Visiting Associate in Economics*
B.A., University of Ljubljana, 1997; M.A., Universidad Autonoma de Barcelona, 2000; Ph.D., California Institute of Technology, 2006. Caltech, 2013-15.

Bradford Cornell, *Visiting Professor of Financ*e
A.B., Stanford University, 1970; M.S., 1974; Ph.D., 1975. Professor, Anderson School of Management, University of California (Los Angeles); Director, Bank of America Research Center, University of California (Los Angeles), 1987-. Visiting Associate Professor, Caltech, 1984; Visiting Professor, 2006-07; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015.

Noel Corngold, Ph.D., *Professor of Applied Physics, Emeritus*
A.B., Columbia College, 1949; A.M., Harvard University, 1950; Ph.D., 1954. Professor of Applied Science, Caltech, 1966-74; Professor of Applied Physics, 1974-2002; Professor Emeritus, 2002-.

Fiona Cowie, Ph.D., *Professor of Philosophy*
B.A., University of Sydney, 1987; M.A., Princeton University, 1991; Ph.D., 1993. Instructor, Caltech, 1992-93; Assistant Professor, 1993-98; Associate Professor, 1998-2010; Professor, 2010-.

Frank N Crespilho, *Visiting Associate in Chemistry*
M.S., University of Sao Paulo, 2004; Ph.D., 2007. Caltech, 2013-14.

Brendan P Crill, *Visiting Associate in Physics*
Ph.D., Caltech, 2001. Senior Technical Staff, Jet Propulsion Laboratory, 2008-. Visiting Associate, Caltech, 2008-16.

Bruno Crosignani, *Visiting Professor of Applied Physics and Materials Science Laurea, University of Rome, 1962;*
Lib. Doc., 1971. Professor, University of Aquila, 1987-. Research Fellow, Caltech, 1970-71; Visiting Associate in Electrical Engineering, 1976-78; 1980; 1982-84; Visiting Associate in Applied Physics, 1985-87; 1988-2004; 2014; Visiting Professor, 2001-14.

Michael C Cross, Ph.D., *Professor of Theoretical Physics*
B.A., University of Cambridge, 1972; Ph.D., 1975. Caltech, 1984-.

Marie E Csete, *Visiting Associate in Medical Engineering*
A.B., Princeton University, 1975; M.D., Columbia University, 1979; Ph.D., California Institute of Technology, 2000. Caltech, 1999-2002; 2014-15.

Fred E Culick, Ph.D., *Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion, Emeritus*
S.B., S.M., Massachusetts Institute of Technology, 1957; Ph.D., 1961. Research Fellow in Jet Propulsion, Caltech, 1961-63; Assistant Professor, 1963-66; Associate Professor, 1966-71; Professor, 1971-78; Professor of Applied Physics and Jet Propulsion, 1978-88; Professor of Mechanical Engineering and Jet Propulsion, 1988-1997; Hayman Professor, 1997-2004; Professor of Jet Propulsion, 1997-2004; Hayman Professor and Professor, Emeritus, 2004-.

Alexandre Cunha, *Lecturer in Biology and and Biological Engineering*
Ph.D., Carnegie Mellon University, 2004. Caltech, 2015.

Thomas Cunningham, *Visiting Associate in Economics*
B.A., Otago University, 1998; Ph.D., London School of Economics, 2012. Caltech, 2014-15.

Curt J Cutler, *Senior Faculty Associate in Physics*
B.S., Yale University, 1983; Ph.D., 1989. Visiting Associate, Caltech, 1999-2006; Senior Faculty Associate, 2006-.

Jaksa Cvitanic, Ph.D., *Richard N. Merkin Professor of Mathematical Finance*
B.A., University of Zagreb (Croatia), 1985; M.S., 1988; M.Phil., Columbia University, 1991; Ph.D., 1992. Professor, Caltech, 2005-13; Merkin Professor, 2013-.

John O Dabiri, Ph.D., *Professor of Aeronautics and Bioengineering; Dean of Undergraduate Students*
B.S., Princeton University, 2001; M.S., Caltech, 2003; Ph.D., 2005. Assistant Professor, Caltech, 2005-09; Associate Professor, 2009-10; Professor, 2010-; Dean of Undergraduate Students, 2014-.

Melissa Dabiri, *Lecturer in Engineering*
B.A, Azusa Pacific University, 2001; M.A., 2004; Ph.D., 2011. Caltech, 2014.

Nathan F Dalleska, *Lecturer in Chemistry*
M.S., University of Minnesota, 1988; Ph.D., University of Utah, 1993. Lecturer in Environmental Science and Engineering, Caltech, 2003-06; Lecturer in Chemistry, 2008; 2009; 2010; 2011; 2014.

Chiara Daraio, Ph.D., *Professor of Aeronautics and Applied Physics*
B.S.; M.S., University of Ancona (Italy), 2001; M.S., University of California (San Diego), 2003; Ph.D., 2006. Assistant Professor, Caltech, 2006-10; Professor, 2011-.

Eric H Davidson, Ph.D., *Norman Chandler Professor of Cell Biology*
B.A., University of Pennsylvania, 1958; Ph.D., Rockefeller University, 1963. Visiting Assistant Professor of Biology, Caltech, 1970; Associate Professor, 1971-74; Professor, 1974-81; Chandler Professor, 1982-.

Gregory L Davis, *Lecturer in Aerospace*
B.S., University of Akron, 1982; M.S., 1982; Ph.D., Rice University, 1998. Caltech, 2006-15.

Mark E Davis, Ph.D., *Warren and Katharine Schlinger Professor of Chemical Engineering*
B.S., University of Kentucky, 1977; M.S., 1978; Ph.D., 1981. Professor, Caltech, 1991-93; Schlinger Professor, 1993-. Executive Officer for Chemical Engineering, 1999-2004.

Peter K Day, *Visiting Associate in Physics*
B.S., University of California, 1988; Ph.D., Caltech, 1993. Senior Engineer, Jet Propulsion Laboratory, 2003-. Lecturer, Caltech, 1993; Research Fellow, 1993-94; Visiting Associate, 2005-16.

Richard A Dean, Ph.D., *Professor of Mathematics, Emeritus*
B.S., Caltech, 1945; A.B., Denison University, 1947; M.S., Ohio State University, 1948; Ph.D., 1953. Harry Bateman Research Fellow, Caltech, 1954-55; Assistant Professor, 1955-59; Associate Professor, 1959-66; Professor, 1966-86; Professor Emeritus, 1987-.

Marios D Demetriou, *Research Professor of Applied Physics and Materials Science*
B.S., University of Arizona, 1995; M.S., University of California (Los Angeles), 1997; Ph.D., 2001. Caltech, Research Professor 2007-.

Semra Demirel-Frank, *Harry Bateman Research Instructor in Mathematics*
M.Sc., University of Stuttgart, 2007; Ph.D., 2012. Caltech, 2013-16.

Tracy K Dennison, Ph.D., *Professor of Social Science History*
B.A., Bucknell University, 1992; M.Phil., University of Oxford, 1999; Ph.D., University of Cambridge, 2004. Assistant Professor, Caltech, 2006-09; Associate Professor, 2009-11; Professor, 2011-.

Peter B Dervan, Ph.D., *D.Sc.h.c., Bren Professor of Chemistry*
B.S., Boston College, 1967; Ph.D., Yale University, 1972; D.Sc.h.c., Boston College. Assistant Professor, Caltech, 1973-79; Associate Professor, 1979-82; Professor, 1982-88; Bren Professor, 1988-. Chair, Division of Chemistry and Chemical Engineering, 1994-99; Vice President for Development and Institute Relations, 2011-12.

Mathieu Desbrun, Ph.D., *John W. and Herberta M. Miles Professor of Computing and Mathematical Sciences; Executive Officer for Computing and Mathematical Sciences*
M.Eng., National Engineering School of Computer Science and Applied Mathematics (Grenoble), 1994; M.S., University of

Grenoble, 1994; Ph.D., National Polytechnic Institute of Grenoble, 1997. Visiting Associate, Caltech, 2000-04; Associate Professor, 2004-09; Professor, 2009-13; Miles Professor, 2013-; Director of Information Science and Technology, 2009-12; Director of Computing and Mathematical Sciences, 2009-14; Executive Officer for Computing and Mathematical Sciences, 2014-.

Stanley Deser, *Visiting Associate in Theoretical Physics*
M.A., Harvard University, 1950; Ph.D., 1953. Ancell Professor, Brandeis University, 1980-. Caltech, 2005-16.

Raymond J (Ray) Deshaies, Ph.D., *Professor of Biology; Investigator, Howard Hughes Medical Institute; Executive Officer for Molecular Biology*
B.S., Cornell University, 1983; Ph.D., University of California, 1988. Assistant Professor, Caltech, 1994-99; Associate Professor, 2000-05; Professor, 2005-. Assistant Investigator, Howard Hughes Medical Institute, 2000-05; Investigator, 2005-. Executive Officer, 2006-.

Mamadou S Diallo, *Visiting Associate in Environmental Science and Engineering*
B.S., Ecole Nationale de l'Induetrie Minerale, 1981; MS.c, Colorado School of Mines, 1987; MS.c, University of Michigan (Ann Arbor), 1993; Ph.D., 1995. Caltech 2010-15.

Yanyan Diao, *Visiting Associate in Chemistry*
B.A., Anhui University of Sciences and Technology, Ph.D., Institute of Process Engineering, Chinese Academy of Science, 2009. Caltech, 2015-16.

Michael H Dickinson, Ph.D., *Esther M. and Abe M. Zarem Professor of Bioengineering*
Sc.B., Brown University, 1984; Ph.D., University of Washington, 1989. Visiting Associate, Caltech, 2001-02; Professor, 2002-03; Zarem Professor, 2003-.

Paul Dimotakis, Ph.D., *John K. Northrop Professor of Aeronautics and Professor of Applied Physics*
B.S., Caltech, 1968; M.S., 1969; Ph.D., 1973. Research Fellow, 1973-74; Research Fellow and Lecturer, 1974-75; Assistant Professor, 1975-81; Associate Professor, 1981-85; Professor, 1986-95; Northrop Professor, 1995-; Jet Propulsion Laboratory Chief Technologist, 2006-11.

Lance Dixon, *Visiting Associate in High Energy Physics*
B.S., California Institute of Technology, 1982; Ph.D., Princeton University, 1986. Caltech, 2015.

Stanislav G (George) Djorgovski, Ph.D., *Professor of Astronomy; Director, Center for Data Driven Discovery*
B.A., University of Belgrade, 1979; M.A., University of California, 1981; Ph.D., 1985. Assistant Professor, Caltech, 1987-90; Associate Professor, 1990-97; Professor, 1997-; Director, Center for Data Driven Discovery, 2014-.

Ciro Donalek, *Lecturer in Biology and Biological Engineering*
M.S., University Federicoll (Naples), 2001; Ph.D, 2007. Caltech, 2013, 2015.

Olivier P Dore, *Visiting Associate in Theoretical Astrophysics*
Ph.D., Institute d'Astrophysique de Paris, 2001. Caltech 2010-16.

David Doty, *Senior Research Fellow in Computing & Mathematical Sciences*
Ph.D., Iowa State University, 2009. Caltech, 2014-.

Dennis A Dougherty, Ph.D., *George Grant Hoag Professor of Chemistry*
B.S., M.S., Bucknell University, 1974; Ph.D., Princeton University, 1978. Assistant Professor, Caltech, 1979-85; Associate Professor, 1985-89; Professor, 1989-2001; Hoag Professor, 2002-. Executive Officer for Chemistry, 1994-99.

Charles D Dowell, *Visiting Associate in Physics; Lecturer in Physics*
B.S., Rice University, 1991; M.S., University of Chicago, 1992; Ph.D., 1997. Scientist, Jet Propulsion Laboratory, 2003-. Visiting Associate, Caltech, 2003-16; Lecturer, 2007; 2008; 2009; 2010; 2011-13.

John C Doyle, Ph.D., *Jean-Lou Chameau Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering*
B.S., M.S., Massachusetts Institute of Technology, 1977; Ph.D., University of California, 1984. Visiting Assistant Professor of Electrical Engineering, Caltech, 1985; Visiting Associate Professor, 1986; Visiting Associate in Chemistry, 1986-87; Associate Professor of Electrical Engineering, 1987-91; Professor, 1991-2001; Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering, 2002-04; Braun Professor, 2004-08; 2009-13; Jean-Lou Chameau Professor, 2013-.

Ronald W Drever, Ph.D., *Professor of Physics, Emeritus*
B.Sc., Glasgow University, 1953; Ph.D., 1958. Visiting Associate, Caltech, 1977; Professor, 1979-2002; Professor Emeritus, 2002-.

William G Dunphy, Ph.D., *Grace C. Steele Professor of Biology*
A.B., Harvard College, 1980; Ph.D., Stanford University, 1985. Assistant Professor, Caltech, 1989-95; Associate Professor, 1995-2001; Professor, 2001-08; Steele Professor, 2008-. Assistant Investigator, Howard Hughes Medical Institute,1994-98; Associate Investigator, Howard Hughes Medical Institute,1998-2004.

Frederick D Eberhardt, Ph.D., *Professor of Philosophy*
B.S., London School of Economics, 2002; M.S., Carnegie Mellon University, 2005; Ph.D., 2007. Caltech, 2013-.

Bertrand Echenard, *Research Professor of High Energy Physics*
Ph.D., Geneva University, 2005. Caltech, 2009-.

Federico M Echenique, Ph.D., *Professor of Economics; Executive Officer for the Social Sciences Licenciado, University of the Republic (Uruguay), 1995;*
Ph.D., University of California, Berkeley, 2000. Instructor, Caltech, 2002-03; Assistant Professor, 2004; Associate Professor, 2004-10; Professor, 2010-; Executive Officer, 2013-.

Michelle Effros, Ph.D., *George Van Osdol Professor of Electrical Engineering*
B.S., Stanford University, 1989; M.S., 1990; Ph.D., 1994. Assistant Professor, Caltech, 1994-2000. Associate Professor, 2000-05; Professor, 2005-13; Van Osdol Professor, 2013-.

Bethany L Ehlmann, Ph.D., *Assistant Professor of Planetary Science; Jet Propulsion Laboratory Research Scientist*
A.B., Washington University in St. Louis, 2004; M.Sc., University of Oxford, 2005; M.Sc., 2007; M.S., Brown University, 2008; Ph.D., 2010. Assistant Professor, Caltech, 2011-; Jet Propulsion Laboratory Research Scientist, 2011-.

Tim F Eifler, *Visiting Associate in Physics*
Ph.D., University of Bonn, 2009. Caltech, 2015-16.

Gerald Eigen, *Visiting Associate in Physics Dipl., University of Freiburg (Germany), 1980;*
Ph.D., University of Munich, 1985. Professor, University of Bergen (Norway), 1995-. Research Fellow, Caltech, 1984-87; Senior Research Fellow, 1987-94; Lecturer, 1991; 1993; Visiting Associate, 1994-2015.

John M Eiler, Ph.D., *Robert P. Sharp Professor of Geology and Professor of Geochemistry*
B.S., University of Iowa, 1989; M.S., University of Wisconsin (Madison), 1991; Ph.D., 1994. Research Fellow, Caltech, 1994-97; Senior Research Fellow 1997-98; Assistant Professor, 1998-2003; Associate Professor, 2003-06; Professor, 2006-; Sharp Professor, 2008-.

James P (Jim) Eisenstein, Ph.D., *Frank J. Roshek Professor of Physics and Applied Physics A.B., Oberlin College, 1974;*
Ph.D., University of California, 1980. Professor of Physics, Caltech, 1996-2004; Roshek Professor, 2004-05; Roshek Professor of Physics and Applied Physics, 2005-.

Charles Elachi, Ph.D., D.Sc.h.c., *Vice President; Director of the Jet Propulsion Laboratory; Professor of Electrical Engineering and Planetary Science*
B.Sc., University of Grenoble, 1968; Dipl. Ing., National Polytechnical Institute (Grenoble), 1968; M.S., Caltech, 1969; Ph.D., 1971; M.B.A., University of Southern California, 1978; D.Sc.h.c., Occidental College. Research Fellow, Caltech, 1971-73; Lecturer in Electrical Engineering, 1982-88; Lecturer in Electrical Engineering and Planetary Science, 1988-2001; Professor, 2002-. Vice President and Director, 2001-.

Matthew P Elgart, *Lecturer in Guitar*
B.F.A., University of California (Los Angeles), 1983; M.F.A., 1985; D.M.A., Claremont Graduate School, 1996. Caltech, 2007-15.

Charles-Othman S (Othman Charles) El-Hamouz, *Visiting Associate in Chemistry*
B.Sc., Jordan University of Science and Technology, 2001; M.Sc., Jordan University, 2004; Ph.D., King Fahd University Petroleum and Minerals, 2013. Caltech, 2015.

H E Ellersieck, Ph.D., *Associate Professor of History, Emeritus*
A.B., University of California (Los Angeles), 1942; M.A., 1948; Ph.D., 1955. Instructor, Caltech, 1950-55; Assistant Professor, 1955-60; Associate Professor, 1960-88; Associate Professor Emeritus, 1988-.

Matthew L Elliott, Ph.D., *Assistant Professor of Economics*
B.A., Oxford University, 2002; MPhil., 2004; Ph.D., Stanford University, 2011. Visiting Associate, Caltech, 2012; Assistant Professor, 2012-.

Richard S Ellis, D.Phil., D.Sc.h.c., *Steele Family Professor of Astronomy*
B.Sc., University College (London), 1971; D. Phil., University of Oxford, 1974; D.Sc.h.c., University of Durham. Visiting Associate, Caltech, 1997-98; Professor, 1999-2002; Steele Professor, 2002-. Deputy Director, Palomar Observatory, 1999-2000; Director, 2000-02; Director, Caltech Optical Observatories, 2002-05.

Michael B Elowitz, Ph.D., *Professor of Biology and Bioengineering; Investigator, Howard Hughes Medical Institute; Executive Officer for Biological Engineering*
B.A., University of California, 1992; M.A., Ph.D., Princeton University, 1999. Assistant Professor, Caltech, 2003-09; Bren Scholar, 2003-09; Associate Professor, 2009-10; Professor, 2010-; Investigator, 2008-; Executive Officer, 2013-.

Azita Emami, Ph.D., *Professor of Electrical Engineering*
B.S., Sharif University of Technology, 1996; M.S., Stanford University, 1999; Ph.D., 2004. Assistant Professor, Caltech, 2007-13; Professor, 2013-.

Manuel A Endres, *Visiting Associate in Physics*
M.S., University of Marburg, 2008; Ph.D., LMU Munich, 2013. Caltech, 2015-16.

Hermann Engelhardt, *Senior Research Associate in Geophysics, Emeritus Dipl., Technical University of Munich, 1960;* Dr.rer.nat., 1974. Senior Research Fellow, Caltech, 1976-79; Visiting Associate, 1981; Senior Research Associate, 1988-2002; Senior Research Associate Emeritus, 2002-.

Jean E Ensminger, Ph.D., *Edie and Lew Wasserman Professor of Social Sciences*
B.A., Cornell University, 1974; M.A., Northwestern University, 1976; Ph.D., 1984. Professor of Anthropology, Caltech, 2000-07; Wasserman Professor of Anthropology, 2007-09; Wasserman Professor, 2009-. Chair, Division of the Humanities and Social Sciences, 2002-06.

Oliver W Eslinger, *Head Coach of Men's Basketball and Physical Education Instructor*
B.A., Clark University, 1997; Ed.M., Boston University, 1999; Ed.D., 2002. Caltech, 2008-.

Thomas E (Tom) Everhart, Ph.D., D.L.h.c., D.h.c., *President Emeritus; Professor of Electrical Engineering and Applied Physics, Emeritus*
A.B., Harvard College, 1953; M.Sc., University of California (Los Angeles), 1955; Ph.D., University of Cambridge, 1958; D.L.h.c., Illinois Wesleyan University; Pepperdine University; D.h.c., Colorado School of Mines. Professor, Caltech, 1987-99; Professor Emeritus, 1999-. President, 1987-97; President Emeritus, 1997-.

Michael J Ewens, Ph.D., *Associate Professor of Finance and Entrepreneurship*
B.A., Washington University in St. Louis, 2004; M.A., University of California, San Diego, 2008; Ph.D., 2010. Caltech, 2014-.

Katherine T Faber, Ph.D., *Simon Ramo Professor of Materials Science*
B.S., Alfred University, 1975; M.S., The Pennsylvania State University, 1978; Ph.D., University of California, Berkeley, 1982. Ramo Professor, Caltech, 2014-.

Wenhao Fan, *Visiting Associate in Applied Physics and Materials Science*
B.S., Tianjing University, 2001; M.S., Uai Yuan University of Technology, 2007; Ph.D., 2013. Caltech, 2014-15.

Andrei Faraon, Ph.D., *Assistant Professor of Applied Physics and Materials Science*
B.S., California Institute of Technology, 2004; M.S., Stanford University, 2009; Ph.D., 2009. Visiting Associate, Caltech, 2011-12; Assistant Professor, 2012-.

Kenneth A Farley, Ph.D., *W.M. Keck Foundation Professor of Geochemistry*
B.S., Yale University, 1986; Ph.D., University of California (San Diego), 1991. Assistant Professor, Caltech, 1993-96; Associate Professor, 1997-98; Professor, 1998-2003; Keck Foundation Professor, 2003-. Director, Tectonic Observatory, 2003-04; Division Chair, 2004-14.

James Farrell, *Lecturer in Computing and Mathematical Sciences*
B.A., Reed College, 1997; M.S., California State University, East Bay, 2006,. Caltech, 2013; 2014; 2015.

Farzad Fathizadeh, *Olga Taussky and John Todd Instructor in Mathematics*
B.S., Sharif University of Technology, 2003; M.S., 2005; Ph.D., University of Western Ontario, 2010. Caltech, 2015-18.

Mordechai Feingold, D.Phil., *Professor of History*
B.A., Hebrew University of Jerusalem, 1972; M.A., 1976; D.Phil., University of Oxford, 1980. Visiting Associate Professor, Caltech, 1994. Professor, 2002-.

Antony R (Tony) Fender, *Lecturer in Engineering*
B.S., University of California (Los Angeles), 1970. Caltech, 1996-2015.

John Fielden, *Visiting Associate in Chemistry*
M.S, University of Bristol, 2000; Ph.D., University of Glasgow, 2004. Caltech, 2015.

Pavel Fileviez Perez, *Visiting Associate in Physics*
Ph.D., Max-Planck Institute for Physics, 2003. Caltech, 2012-15.

Bradley W Filippone, Ph.D., *Professor of Physics*
B.S., Pennsylvania State University, 1977; M.S., University of Chicago, 1979; Ph.D., 1982. Research Fellow, Caltech, 1983-84; Assistant Professor, 1984-90; Associate Professor, 1990-95; Professor, 1995-.

Woodward Fischer, Ph.D., D.h.c., *Professor of Geobiology*
B.A., Colorado College, 2000; Ph.D., Harvard University, 2007; D.h.c., Colorado College. Assistant Professor, Caltech, 2009-14; Professor, 2014-.

Matthias Flach, Ph.D., *Professor of Mathematics Dipl., Johann-Wolfgang von Goethe University (Frankfurt), 1986;* Ph.D., St. John's College, 1991. Associate Professor, Caltech, 1995-99; Professor, 1999-. Executive Officer for Mathematics, 2006-09.

Richard C Flagan, Ph.D., *Irma and Ross McCollum-William H. Corcoran Professor of Chemical Engineering and Environmental Science and Engineering*
B.S.E., University of Michigan, 1969; S.M., Massachusetts Institute of Technology, 1971; Ph.D., 1973. Assistant Professor of Environmental Engineering Science, Caltech, 1975-81; Associate Professor, 1981-84; Associate Professor of Environmental

Engineering and Mechanical Engineering, 1984-85; Professor, 1986-90; Professor of Chemical Engineering, 1990-2000; McCollum Professor of Chemical Engineering, 2000-03; McCollum Professor of Chemical Engineering and Professor of Environmental Science and Engineering, 2003-04; McCollum-Corcoran Professor of Chemical Engineering and Environmental Science and Engineering, 2004-. Acting Executive Officer for Chemical Engineering, 1996; Executive Officer, 1997; 2004-13.

Stephen J Forman, *Visiting Associate in Chemical Engineering*
B.A., St. John's College, 1970; M.D., University of Southern California, 1974. Staff Physician and Chairman of the Board of Directors, City of Hope, 2001-. Caltech, 2005-14.

Alessandro (Al) Fortunelli, *Visiting Associate in Chemistry*
M.S., University of Pisa, 1983. First Researcher, Instituto per i Processi Chimico-Fisici, 1984-. Caltech, 2003-04; 2012-15.

Trevor Y Foucher, *Lecturer in Computing and Mathematical Sciences*
B.S., University of California, Berkeley, 1998. Caltech, 2014; 2015.

Elisa Franco, *Visiting Associate in Computing and Mathematical Sciences*
M.S., University of Trieste, Italy, 2002; Ph.d., 2007; Ph.D., California Institute of Technology, 2011. Caltech 2011-15.

Rupert L Frank, Ph.D., *Professor of Mathematics*
Dipl., Ludwig-Maximilians-Universitat Munich, 2003; Ph.D., Royal Institute of Technology, 2007. Caltech, 2013-.

Christian Frankenberg, Ph.D., *Associate Professor of Environmental Science and Engineering*
B.S., University of Bayreuth, 2002; Ph.D., Ruprecht-Karls-Universitat Heidelberg, 2005. Caltech, 2015-.

J N Franklin, Ph.D., *Professor of Applied Mathematics, Emeritus*
B.S., Stanford University, 1950; Ph.D., 1953. Associate Professor of Applied Mechanics, Caltech, 1957-65; Professor of Applied Science, 1965-69; Professor of Applied Mathematics, 1969-2000; Professor Emeritus, 2000-

Scott E Fraser, *Visiting Associate in Biology and Biological Engineering*
B.S., Harvey Mudd College, 1976; Ph.D., Johns Hopkins University, 1979. Professor of Biology, Caltech, 1991; Rosen Professor, 1991-; Professor of Bioengineering, 2005-. Director, Magnetic Resonance Imaging Center, 2002-08; Director, Rosen Bioengineering Center, 2008-12. Caltech 2013-15.

Steven C Frautschi, Ph.D., *Professor of Theoretical Physics, Emeritus*
A.B., Harvard College, 1954; Ph.D., Stanford University, 1958. Assistant Professor, Caltech, 1962-64; Associate Professor, 1964-66; Professor, 1966- 2006; Professor Emeritus, 2006-. Executive Officer for Physics, 1988-97; Master of Student Houses, 1997-2002.

Stuart Freed, *Lecturer in Art -Ceramics*
B.A., California State University (Northridge), 1979. Caltech, 1999-2015.

Anthony Freeman, *Lecturer in Aerospace*
B.S., University of Manchester, United Kingdom, 1979; Ph.D., 1982. Caltech, 2013-15.

Amanda Y Friedenberg, *Visiting Associate in Economics*
B.A., New York University, 1998; Ph.D., Harvard University, 2003. Caltech, 2015.

Cary D Frydman, *Visiting Associate in Economics*
B.A., Northwestern University, 2006; M.S., Caltech, 2009; Ph.D., 2012. Caltech, 2013-15.

Gregory C Fu, Ph.D., *Altair Professor of Chemistry*
B.S., Massachusetts Institute of Technology, 1985; Ph.D., Harvard University, 1991. Moore Distinguished Scholar, Caltech, 2011; Altair Professor, 2012-.

Thomas Fuchs, *Lecturer in Mechanical and Civil Engineering*
M.S., Gratz College, 2005; Ph.D., Swiss Federal Institute of Technology, 2010. Caltech, 2015.

Brent Fultz, Ph.D., *Barbara and Stanley R. Rawn, Jr., Professor of Materials Science and Applied Physics*
B.Sc., Massachusetts Institute of Technology, 1975; M.Sc., University of California, 1978; Ph.D., 1982. Assistant Professor, Caltech, 1985-90; Associate Professor, 1990-97; Professor of Materials Science, 1997-2002; Professor of Materials Science and Applied Physics, 2003-13; Rawn Professor, 2013-.

Deborah K Fygenson, *Visiting Associate in Electrical Engineering*
B.S., Massachusetts Institute of Technology, 1989; M.S., Princeton University, 1991; Ph.D., 1995. Caltech, 2012-14.

Todd C Gaier, *Faculty Associate in Physics*
Ph.D., University of California (Santa Barbara), 1993. Principal Staff, Jet Propulsion Laboratory, 1996-. Caltech, 2004-15.

Mandy Gamble, *Head Coach of Men's and Women's Tennis and Physical Education Instructor*
B.A., California State University, 1995; M.A., 1997. Caltech, 2002-.

Daniel A Garcia, *Lecturer in Spanish Lic., National University of Columbia, 1988;*
M.A., University of Southern California, 1991. Caltech, 1996-2018.

Carol M Garland, *Lecturer in Applied Physics and Materials Science*
B.A., University of Vermont, 1967. Caltech, 2013-15.

George R Gavalas, Ph.D., *Professor of Chemical Engineering, Emeritus*
B.S., Technical University of Athens, 1958; M.S., University of Minnesota, 1962; Ph.D., 1964. Assistant Professor, Caltech, 1964-67; Associate Professor, 1967-75; Professor, 1975-2002; Professor Emeritus, 2002-.

Vikram Gavini, *Visiting Associate in Mechanical and Civil Engineering*
M.S., California Institute of Technology, 2004; Ph.D., 2007. Caltech, 2015.

John B Geasland, *Lecturer in English as a Second Language*
B.S.F.S., Georgetown University, 1966. Caltech, 2001-16.

Murray Gell-Mann, Ph.D., Sc.D.h.c., D.Sc.h.c., *Robert Andrews Millikan Professor of Theoretical Physics, Emeritus*
B.S., Yale University, 1948; Ph.D., Massachusetts Institute of Technology, 1950; Sc.D.h.c., Columbia University; University of Cambridge; University of Chicago; University of Illinois; University of Utah; Wesleyan University; Yale University; D.Sc.h.c., University of Turin (Italy). Associate Professor, Caltech, 1955-56; Professor, 1956-67; Millikan Professor, 1967-93; Millikan Professor Emeritus, 1993-.

Glen A George, *Lecturer in Electrical Engineering*
B.S. (Engineering and Applied Science), Caltech, 1981; B.S. (Electrical Engineering), 1982; M.S., University of California (Los Angeles), 1984. Lecturer in Applied Science, Caltech, 1986-1991; Lecturer in Computer Science and Electrical Engineering, 1992-2017.

Thomas George, *Visiting Associate in Physics*
B.Tech., Indiana Institute of Technology, Madras, 1982; M.S., University of California, Berkeley, 1984; Ph.D., 1989. Caltech, 2010-12; 2013-15.

Merrill J Gerber, *Lecturer in Creative Writing*
B.A., University of Florida, 1959; M.A., Brandeis University, 1980. Caltech, 1989-2015.

Alireza Ghaffari, *Lecturer in Applied Physics and Materials Science* B.S., California State University, 1986; M.S., Caltech, 2008. Lecturer, 2005-09; 2010-15.

Morteza Gharib, Ph.D., *Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Ronald and Maxine Linde Institute of Economic and Management Sciences; Vice Provost*
B.S., Teheran University, 1976; M.S., Syracuse University, 1978; Ph.D., Caltech, 1983. Professor of Aeronautics, 1992-2001; Professor of Aeronautics and Bioengineering, 2001-02; Liepmann Professor of Aeronautics and Bioengineering, 2002-06; Professor of Bioengineering, 2006-09; Professor of Bioinspired Engineering, 2009-13; Liepmann Professor, 2006-; Director, Linde Institute, 2014-; Vice Provost, 2010-.

Konstantinos P Giapis, Ph.D., *Professor of Chemical Engineering Dipl., National Technical University of Athens, 1984;*
Ph.D., University of Minnesota, 1989. Lacey Instructor, Caltech, 1992-93; Assistant Professor, 1993-98; Associate Professor, 1999-2010; Professor, 2010-.

Benjamin J (Ben) Gillen, Ph.D., *Assistant Professor of Economics*
B.A., Yale University, 1999; Ph.D., University of California, San Diego, 2010; Caltech, 2010-.

Kevin M Gilmartin, Ph.D., *Professor of English B.A., Oberlin College, 1985;*
M.A., University of Chicago, 1986; Ph.D., 1991. Assistant Professor, Caltech, 1991-97; Associate Professor of Literature, 1997-2004; Associate Professor of English, 2004-07; Professor, 2007-.

Dehn Gilmore, Ph.D., *Professor of English*
B.A., Harvard University, 2002; M.Phil., University of Cambridge (Trinity College), 2003; M.Phil., Columbia University, 2005; Ph.D., 2009. Assistant Professor, Caltech, 2009-15; Professor, 2015-.

Jan P Glascher, *Visiting Associate in Psychology*
Ph.D., University of Hamburg, 2005. Caltech, 2010-14.

William A Goddard, Ph.D., *Charles and Mary Ferkel Professor of Chemistry, Materials Science, and Applied Physics*
B.S., University of California (Los Angeles), 1960; Ph.D., Caltech, 1965. Noyes Research Fellow in Chemistry, 1964-66; Noyes Research Instructor, 1966-67; Assistant Professor of Theoretical Chemistry, 1967-71; Associate Professor, 1971-74; Professor, 1974-78; Professor of Chemistry and Applied Physics, 1978-84; Ferkel Professor of Chemistry, 1984-2001; Ferkel Professor of Chemistry, Materials Science, and Applied Physics, 2001-.

Lea A Goentoro, Ph.D., *Assistant Professor of Biology*
B.S., University of Wisconsin-Madison, 2001; Ph.D., Princeton University, 2006. Caltech, 2011-.

Peter Goldreich, Ph.D., *Lee A. DuBridge Professor of Astrophysics and Planet*ary Physics, Emeritus

B.S., Cornell University, 1960; Ph.D., 1963. Associate Professor of Planetary Science and Astronomy, Caltech, 1966-69; Professor, 1969-81; DuBridge Professor of Astrophysics and Planetary Physics, 1981-2002; DuBridge Professor Emeritus, 2002-. Acting Chairman, Division of Geological and Planetary Sciences, 1989.

Paul F Goldsmith, *Visiting Associate in Astronomy*
A.B., University of California, 1969; Ph.D., 1975. Principal Scientist, Jet Propulsion Laboratory, 2005-. Caltech, 2006-16.

Matthew Golombek, *Lecturer in Planetary Science; Visiting Asso*ciate Planetary Science
A.B., Rutgers College, 1976; M.S., University of Massachusetts, 1978; Ph.D., 1981. Caltech, 2012-16.

James D Goltz, *Visiting Associate in Mechanical* and Civil Engineering
B.S., Ohio State University, 1970; M.S., 1976; Ph.D., University of California, Los Angeles, 2006. Caltech, 2013-15.

Sunil Golwala, Ph.D., *Professor of Physics; Director, Caltech Submillimeter Observatory*
B.A., University of Chicago, 1993; M.A., University of California, Berkeley, 1995; Ph.D., 2000. Assistant Professor, Caltech, 2003-10; Associate Professor, 2010; Professor, 2010-; Director, Caltech Submillimeter Observatory, 2013-.

Gabriela Gonzalez, *Visiting Associate in Physics*
Ph.D., Syracuse University, 1995. Caltech, 2008-14.

David L Goodstein, Ph.D., *Frank J. Gilloon Distinguished Teaching and Service Professor, Emeritus; Professor of Physics and Applied Physics, Emeritus*
B.S., Brooklyn College, 1960; Ph.D., University of Washington, 1965. Research Fellow in Physics, Caltech, 1966-67; Assistant Professor, 1967-71; Associate Professor, 1971-75; Associate Professor of Physics and Applied Physics, 1975-76; Professor, 1976-2009; Gilloon Professor, 1995-2009; Gilloon Professor Emeritus, 2009-. Vice Provost, 1987-2007.

Judith R Goodstein, Ph.D., *University Archivist, Emeritus*
B.A., Brooklyn College, 1960; Ph.D., University of Washington, 1969. Faculty Associate, Caltech, 1982-2009; Lecturer, 1989; 2001; 2002; 2007. Registrar, 1989-2003; Institute Archivist, 1968-95; University Archivist, 1995-2009; University Archivist, Emeritus, 2009-.

Roy W Gould, Ph.D., *Simon Ramo Professor of Engineering, Emeritus*
B.S., Caltech, 1949; M.S., Stanford University, 1950; Ph.D., Caltech, 1956. Assistant Professor of Electrical Engineering, 1955-58; Associate Professor, 1958-60; Associate Professor of Electrical Engineering and Physics, 1960-62; Professor, 1962-74; Professor of Applied Physics, 1974-80; Ramo Professor of Engineering, 1980-96; Ramo Professor Emeritus, 1996-. Executive Officer for Applied Physics, 1973-79; Chairman, Division of Engineering and Applied Science, 1979-85.

Thomas B Graber, Ph.D., *Professor of Mathematics*
A.B., Harvard, 1994; M.A. University of California (Los Angeles), 1995; Ph.D., 1998. Associate Professor, Caltech, 2005-08; Professor, 2008-.

Viviana Gradinaru, Ph.D., *Assistant Professor of Biology and Biological Engineering*
B.S., California Institute of Technology, 2005; Ph.D., Stanford University, 2010. Visiting Associate, Caltech, 2012; Assistant Professor, 2012-.

Keith J Grainge, *Visiting Associate in Physics*
Ph.D., University of Cambridge, 1996. Senior Research Associate, 2004-. Caltech, 2008-13; 2014-15.

Jeffrey Gralnick, *Visiting Professor of Geobiology*
B.A., University of Colorado, 1997; Ph.d., University of Wisconsin, 2003, Associate Professor, University of Minnesota, 2005-; Caltech, 2015.

Mark Graves, *Visiting Associate in Psychology*
B.S., University of Miami, 1985; M.S., Georgia Institute of Technology; Ph.D., University of Michigan, Ann Arbor, 1993; M.A., Jesuit School of Theology, 2005. Caltech, 2013-15.

Robert W Graves, *Visiting Associate in Geophysics*
B.S, University of California, Riverside, 1984; M.S., California Institute of Technology, 1988; Ph.D., 1990. Caltech, 2012-14; 2015.

Harry B Gray, Ph.D., D.Sc.h.c., D.L.h.c., *Arnold O. Beckman Professor of Chemistry; Founding Director, Beckman Institute*
B.S., Western Kentucky College, 1957; Ph.D., Northwestern University, 1960; D.Sc.h.c., Northwestern University; University of Rochester; University of Chicago; Göteborg University; University of Pennsylvania; Bowling Green State University; University of Arizona; Laurea h.c., University of Florence; D.L.h.c., Illinois Wesleyan University. Visiting Professor of Inorganic Chemistry, Caltech, 1965; Professor of Chemistry, 1966-81; William R. Kenan Professor, 1976-81; Beckman Professor, 1981-. Chairman, Division of Chemistry and Chemical Engineering, 1978-84; Director, Beckman Institute, 1986-2001; Founding Director, 2001-.

Julia R Greer, Ph.D., *Professor of Materials Science and Mechanics*
B.S., Massachusetts Institute of Technology, 1997; M.S., Stanford University, 2000; Ph.D., Stanford University, 2005. Assistant Professor, Caltech, 2007-13; Professor, 2013-.

David M Grether, Ph.D., *Frank J. Gilloon Professor of Economics, Emeritus*
B.S., University of California, 1960; Ph.D., Stanford University, 1969. Associate Professor, Caltech, 1970-75; Professor, 1975-2009; Gilloon Professor, 2009-10; Gilloon Professor, Emeritus, 2010-. Executive Officer for Social Sciences, 1978-82; Chairman, Division of the Humanities and Social Sciences, 1982-92; Interim Chair, Division of the Humanities and Social Sciences, 2006-07.

Allen R Gross, *Lecturer in Symphony Orchestra*
A.B., Queens College, 1965; M.A., University of California, 1967; D.M.A., Stanford University, 1978. Caltech, 1999-2015.

Zeev Gross, *Moore Distinguished Scholar*
B.Sc., Bar-Ilan University (Israel), 1979; M.Sc., 1982; Ph.D., 1987. Visitor, Caltech, 1999, 2009; Visiting Associate, 2011; Moore Distinguished Scholar, 2013-14.

John P Grotzinger, Ph.D., *Fletcher Jones Professor of Geology; Chair, Division of Geological and Planetary Sciences*
B.S., Hobart College, 1979; M.S., University of Montana, 1981; Ph.D., Virginia Polytechnic Institute and State University, 1985. Visiting Associate Professor, Caltech, 1996; Moore Distinguished Scholar, 2004; Fletcher Jones Professor, 2005-; Division Chair, 2014-.

Robert H (Bob) Grubbs, Ph.D., *Victor and Elizabeth Atkins Professor of Chemistry*
B.S., University of Florida, 1963; M.S., 1965; Ph.D., Columbia University, 1968. Professor, Caltech, 1978-90; Atkins Professor, 1990-.

Sergei G Gukov, Ph.D., *Professor of Theoretical Physics and Mathematics*
B.S., Moscow Institute of Physics and Technology, 1997; M.S., Princeton University 2001; Ph.D., 2001. Associate Professor, Caltech, 2005-07; Professor, 2007-.

Chin-Lin Guo, *Visiting Associate in Mechanical Engineering*
B.S., National Taiwan University, 1994; M.S., 1996; Ph.D., University of California (San Diego), 2001. Assistant Professor, 2006-14; Caltech, 2014.

Michael C Gurnis, Ph.D., *John E. and Hazel S. Smits Professor of Geophysics; Director, Seismological Laboratory*
B.S., University of Arizona, 1982; Ph.D., Australian National University, 1987. Associate Professor, Caltech, 1994-96; Professor, 1996-2005. Smits Professor, 2005-. Associate Director, Seismological Laboratory, 1995-2003; Director, 2009-.

Herold R Gustafson, *Visiting Associate in Physics*
B.S., Caltech, 1959; M.S., University of Washington, 1961; Ph.D., 1968. Senior Research Scientist, University of Michigan, 1968-. Visiting Associate, Caltech, 1997-2014.

Mitchell Guttman, Ph.D., *Assistant Professor of Biology*
B.S., University of Pennsylvania, 2006; M.S., 2006; Ph.D., Massachusetts Institute of Technology, 2012. Visiting Associate, Caltech, 2012-13; Assistant Professor, 2013-.

Majid Hadian-Jazi, *Scott Russell Johnson Research Assistant Professor in Mathematics*
B.S., Sharif University of Technology, 2004; M.S., 2006; Ph.D., Max-Planck Institute for Mathematics, 2010. Caltech, 2014-17.

Sang Soo Hah, *Visiting Associate in Chemistry*
B.S., Seoul National University, 1994; Ph.D., 2001. Caltech, 2014-15.

Inseob Hahn, *Visiting Associate in Physics*
B.Sc., Seoul National University, 1985; Ph.D., University of Southern California, 1993. Principal Scientist, Jet Propulsion Laboratory, 2007-. Caltech, 2008-14.

Sossina M Haile, Ph.D., *Carl F Braun Professor of Materials Science and Chemical Engineering*
B.S., Massachusetts Institute of Technology, 1986; M.S., University of California, 1988; Ph.D., Massachusetts Institute of Technology, 1992. Assistant Professor, Caltech, 1996-2001; Associate Professor, 2001-06; Professor, 2006-11; Braun Professor, 2012-.

Christian Hainzl, *Visiting Associate in Mathematics*
Ph.D., University of Vienna, 1999. Caltech, 2014-15.

S A (Ali) Hajimiri, Ph.D., *Thomas G. Myers Professor of Electrical Engineering; Executive Officer for Electrical Engineering; Director, Information Science and Technology*
B.S., Sharif University of Technology, 1994; M.S., Stanford University, 1996; Ph.D., 1998. Assistant Professor, Caltech, 1998-2003; Associate Professor, 2003-06; Professor, 2006-10; Myers Professor, 2010-; Executive Officer, 2015-; Director, Information Science and Technology, 2015-.

John F Hall, Ph.D., *Professor of Civil Engineering*
B.S., West Virginia University, 1972; M.S., University of Illinois, 1973; Ph.D., University of California, 1980. Research Fellow, Caltech, 1980-83; Lecturer, 1981-83; Assistant Professor, 1983-89; Associate Professor,

1989-97; Professor, 1997-. Executive Officer for Civil Engineering and Applied Mechanics, 1998-2005. Dean, 2005-10; Acting Vice President, 2006-07.

Judith Hall, *Lecturer in Creative Writing*
A.B., Clark University, 1973; M.A., Johns Hopkins University, 1979. Caltech, 1999-2006; 2008; 2009, 2011-12; 2013-14; 2015.

Susanne E Hall, *Campus Writing Coordinator in the Hixon Writing Center and Lecturer in Writing (long-term)*
B.A., Wake Forest University, 2001; M.A., University of California, Irvine, 2003; Ph.D., 2008. Caltech, 2012-17.

Gregg W Hallinan, Ph.D., *Assistant Professor of Astronomy*
B.Sc., National University of Ireland, 2002; Ph.D., 2008. Caltech, 2012-.

Seunghoon Han, *Visiting Associate in Applied Physics and Materials Science*
Ph.D., Seoul National University, 2005. Caltech, 2014-16.

Yong Hao, *Visiting Associate in Applied Physics and Materials Science*
B.S., University of Science and Technology of China, 2001; M.S., California Institute of Technology, 2002; Ph.D., 2007. Caltech, 2012-15.

David G Harkrider, Ph.D., *Professor of Geophysics, Emeritus*
B.A., Rice University, 1953; M.A., 1957; Ph.D., Caltech, 1963. Associate Professor, 1970-79; Professor, 1979-95; Professor Emeritus, 1995-. Associate Director, Seismological Laboratory, 1977-79.

John M Harris, *Visiting Associate in Geology*
B.Sc., University of Leicester (United Kingdom), 1964; M.A., University of Texas (Austin), 1967; Ph.D., University of Bristol, 1970. Chief Curator, George C. Page Museum, 1993-. Caltech, 2001-15.

Fiona A Harrison, Ph.D., D.techn.h.c., *Benjamin M. Rosen Professor of Physics; Kent and Joyce Kresa Leadership Chair, Division of Physics, Mathematics and Astronomy*
A.B., Dartmouth College, 1985; Ph.D., University of California, 1993; D.techn.h.c., Danish Technical University. Robert Millikan Research Fellow, Caltech, 1993-95; Assistant Professor of Physics, 1995-99; Assistant Professor of Physics and Astronomy, 1999-2001; Associate Professor 2001-2005; Professor, 2005-13; Rosen Professor, 2013-; Kresa Leadership Chair, 2015-.

Babak Hassibi, Ph.D., *Gordon M. Binder/Amgen Professor of Electrical Engineering*
B.S., University of Tehran, 1989; M.S., Stanford University, 1993; Ph.D, 1996. Assistant Professor, Caltech, 2001-03; Associate Professor, 2003-2008; Professor, 2008-2013; Binder/Amgen Professor, 2013-; Executive Officer, 2008-15; Associate Director, 2010-2012.

Kristine L Haugen, Ph.D., *Professor of English*
B.A., University of Chicago, 1996; M.A., Princeton University, 1998; Ph.D., 2001. Assistant Professor, Caltech, 2005-11; Professor, 2011-.

Egill Hauksson, *Research Professor in Geophysics*
M.S., University of Trondheim (Norway), 1974; M.A., Columbia University, 1978; M. Phil., 1980; Ph.D., 1981. Research Fellow, Caltech, 1989-92; Senior Research Associate, 1992-2014, Research Professor of Geophysics, 2014-.

Bruce A Hay, Ph.D., *Professor of Biology*
B.A., Claremont McKenna College, 1982; Ph.D., University of California (San Francisco), 1989. Assistant Professor, Caltech, 1996-2002; Associate Professor, 2002-08; Professor, 2008-.

Xuelian He, *Visiting Associate in Chemical Engineering*
B.S., East China University of Science & Technology, 2001, M.S., 2004, Ph.D., 2009. Caltech, 2014-15.

Yongning He, *Visiting Associate in Biology and Biological Engineering*
B.S., Fudan University, 1991, M.S., 1994; Ph.D., Purdue Universtiy, 2002. Caltech, 2011-15.

James R Heath, Ph.D., *Elizabeth W. Gilloon Professor and Professor of Chemistry*
B.Sc., Baylor University, 1984; M.A., Rice University, 1988; Ph.D., 1988. Caltech, 2003-.

Thomas H Heaton, Ph.D., *Professor of Engineering Seismology*
B.S., Indiana University, 1972; Ph.D., Caltech, 1978. Visiting Associate in Geophysics, 1980-91; Faculty Associate, 1991-95; Lecturer in Geophysics, 1993-94; Lecturer in Engineering Seismology, 1995; Professor, 1995-.

S. Mohammad Hadi (Hadi) Hedayat Zadeh Razavi, *Harry Bateman Research Instructor in Mathematics*
B.S., École Polytechnique Fédérale de Lausanne, 2004; M.S., 2006; Ph.D., Swiss Federal Institute of Technology, Zurich, 2010. Caltech, 2011-14.

John L Heilbron, *Visiting Associate in History*
A.B., University of California, 1955; M.A., 1958; Ph.D., 1964. Professor, 1994-. Sherman Fairchild Distinguished Scholar, Caltech, 1995; Mellon Visiting Professor, 1997; Eleanor Searle Visiting Professor, 2011; Visiting Associate, 2011-16.

Donald V Helmberger, Ph.D., *Professor of Geophysics*
B.S., University of Minnesota, 1961; M.S., University of California (San Diego), 1965; Ph.D., 1967. Assistant Professor, Caltech, 1970-74; Associate Professor, 1974-79; Professor, 1979-2000, 2011-; Smits Family Professor, 2000-11. Director, Seismological Laboratory, 1998-2003.

Sergi R Hildebrandt, *Visiting Associate in Observational Cosmology; Lecturer in Physics*
Ph.D., University of Barcelona, 2011. Caltech, 2014-16.

Michael G Hill, *Visiting Associate in Chemistry*
B.A., Macalester College, 1987; Ph.D., University of Minnesota, 1992. Assistant Professor, Occidental College, 1994-. Research Fellow, Caltech, 1992-94; Visiting Associate, 1995-2010; 2014-17; Lecturer, 2008.

Lynne Hillenbrand, Ph.D., *Professor of Astronomy*
A.B., Princeton University, 1989; M.S., 1989; Ph.D., University of Massachusetts, 1995. Assistant Professor, Caltech, 2000-06; Associate Professor, 2006-10; Professor, 2010-; Executive Officer, 2007-12.

Steve Hindle, *Visiting Professor of History*
B.A., University of Cambridge, 1986; M.A., University of Minnesota, 1988; Ph.D., University of Cambridge, 1993. Caltech, 2012-16.

Kayoko Hirata, *Lecturer in Japanese*
B.A., Kitakyuushuu University (Japan), 1966; M.A., University of Oregon, 1978; M.A., University of Arizona (Tucson), 1987; Ph.D., 1989. Caltech, 1990-.

Alexander V (Alex) Hirsch, Ph.D., *Associate Professor of Political Science*
B.A., Yale University, 2003; Ph.D., Stanford University, 2010. Caltech, 2014-.

Christopher R Hitchcock, Ph.D., *J. O. and Juliette Koepfli Professor of Philosophy*
A.B., Princeton University, 1986; M.A. (Philosophy); M.A. (Mathematics), University of Pittsburgh, 1990; Ph.D., 1993. Associate Professor, Caltech, 1998-2002; Professor, 2002-14; Koepfli Professor, 2014-.

David G Hitlin, Ph.D., *Professor of Physics*
B.A., Columbia University, 1963; M.A., 1965; Ph.D., 1968. Associate Professor, Caltech, 1979-85; Professor, 1986-.

Andre Hoelz, Ph.D., *Assistant Professor of Biochemistry*
B.Sc., Albert-Ludwigs University of Freiburg, 1993; M.Sc.,1997; Ph.D., Rockefeller University, 2004. Caltech, 2010-.

Philip T Hoffman, Ph.D., *Rea A. and Lela G. Axline Professor of Business Economics and Professor of History*
A.B., Harvard College, 1969; M.A., University of California, 1971; Ph.D., Yale University, 1979. Lecturer in History, Caltech, 1980-81; Instructor, 1981-82; Assistant Professor, 1982-84; Associate Professor of History and Social Science, 1984-95; Professor, 1995-2003; Richard and Barbara Rosenberg Professor of History and Social Science, 2003-08; Axline Professor, 2008-. Executive Officer for the Humanities, 1995-2000.

Michael R Hoffmann, Ph.D., *James Irvine Professor of Environmental Science*
B.A., Northwestern University, 1968; Ph.D., Brown University, 1974. Research Fellow, Caltech, 1973-76; Associate Professor, 1980-85; Professor of Environmental Engineering Science, 1986-90; Professor of Environmental Chemistry, 1990-96; Irvine Professor of Environmental Science, 1996-. Executive Officer for Environmental Engineering Science, 1996-2002; Dean of Graduate Studies, 2002-2009.

Douglas C Hofmann, *Visiting Associate in Applied Physics and Materials Science; Lecturer in Applied Physics and Materials Science*
B.S., University of California, San Diego, 2003; M.S., 2004; M.S., Caltech, 2006; Ph.D., 2008. Caltech, 2011-16.

Christopher E Holmden, *Visiting Associate in Geochemistry*
B.S., McMaster University, 1990; Ph.D., University of Alberta, 1995. Caltech, 2015.

Gerard J Holzmann, *Senior Faculty Associate in Computing and Mathematical Sciences*
B.S., Delft University of Technology (Netherlands), 1973; M.S., 1976; Ph.D., 1979. Lecturer, Caltech, 2003-06; 2008; 2009; 2010; 2013; 2015; Faculty Associate, 2007-2012; Senior Faculty Associate, 2012-.

Philip W Hon, *Visiting Associate in Applied Physics and Materials Science*
B.S., Univesity of California (Los Angeles), 2004; M.S., 2007; Ph.D., 2013. Caltech, 2014-15.

Elizabeth J Hong, Ph.D., *Assistant Professor of Neuroscience*
B.S., California Institute of Technology, 2002; Ph.D., Harvard University, 2009. Visiting Associate, Caltech, 2014-15; Assistant Professor, 2015-.

Eric Hoopfer, *Research Assistant Professor of Biology and Biological Engineering*
B.S., University of Michigan (Ann Arbor), 1999; Ph.D., Stanford University, 2008. Caltech, 2014-.

John J Hopfield, Ph.D., *Roscoe G. Dickinson Professor of Chemistry and Biology, Emeritus*
A.B., Swarthmore College, 1954; Ph.D., Cornell University, 1958. Dickinson Professor, Caltech, 1980-97; Dickinson Professor Emeritus, 1997-.

Philip F Hopkins, Ph.D., *Assistant Professor of Theoretical Astrophysics*
B.A., Princeton University, 2004; M.A., Harvard University, 2005; Ph.D., 2008. Caltech, 2013-.

Hans G Hornung, Ph.D., D.h.c., *C. L. "Kelly" Johnson Professor of Aeronautics, Emeritus*
B.S., University of Melbourne, 1960; M.S., 1962; Ph.D., University of London (Imperial College), 1965; D.h.c., Swiss Federal Institute of Technology. Johnson Professor, Caltech, 1987-2005; Johnson Professor Emeritus, 2005-. Director, Graduate Aeronautical Laboratories, 1987-2004.

Yizhao T (Thomas) Hou, Ph.D., *Charles Lee Powell Professor of Applied and Computational Mathematics*
B.S., South China University of Technology, 1982; M.S., University of California (Los Angeles), 1985; Ph.D., 1987. Associate Professor of Applied Mathematics, Caltech, 1993-98; Professor, 1998-2000; Professor of Applied and Computational Mathematics, 2000-04; Powell Professor, 2004-. Executive Officer for Applied and Computational Mathematics, 2000-06.

Martin Houde, *Visiting Associate in Physics*
Ph.D., University on Montreal, 2001. Caltech 2011-16.

Robert M Housley, *Visiting Associate in Geochemistry*
B.A., Reed College, 1956; Ph.D., University of Washington, 1964. Member of the Technical Staff, Rockwell International Science Center, 1966-. Visiting Professor, Caltech, 1984-85; 1985-86; Visiting Associate, 1986-2004; 2010-15.

James B Howard, *Visiting Associate in Chemistry*
B.A., DePauw University, 1964; Ph.D., University of California (Los Angeles), 1968. Professor, University of Minnesota, 1982-. Caltech, 1996-2016.

Elaine Y Hsiao, *Research Assistant Professor in Biology and Biological Engineering*
B.S., University of California (Los Angeles) 2006; Ph.D., Caltech, 2013. Caltech, 2014-.

David Hsieh, Ph.D., *Assistant Professor of Physics*
B.S., Stanford University, 2003; Ph.D., Princeton University, 2009. Caltech, 2012-.

Linda C Hsieh-Wilson, Ph.D., *Professor of Chemistry*
B.S., Yale University, 1990; Ph.D., University of California, 1996. Assistant Professor, Caltech, 2000-06; Associate Professor, 2006-10; Professor, 2010-; HHMI Investigator, 2005-14.

Ming Hu, *Visiting Associate in Mechanical and Civil Engineering*
B.S., University of Science and Technology, 2001; Ph.D., Institute of Mechanics (CAS), 2007. Caltech, 2014.

Alice S Huang, *Senior Faculty Associate in Biology*
B.A., Johns Hopkins University, 1961; M.S., 1963; Ph.D., 1966. M.A. h.c., Harvard University; D.Sci.h.c., Wheaton College; Mt. Holyoke College; Medical College of Pennsylvania. Faculty Associate, Caltech, 1997-2007; Senior Faculty Associate, 2007-.

Jiangtao Huangfu, *Visiting Associate in Electrical Engineering*
B.S., Zhejiang University, 1999; Ph.D., 2004. Caltech, 2013-15.

Kenneth W Hudnut, *Visiting Associate in Geophysics*
A.B., Dartmouth College, 1983; M.A., Columbia University, 1986; Ph.D., 1989. Geophysicist and Project Chief, U.S. Geological Survey, 1992-. Research Fellow, Caltech, 1989-92; Visiting Associate, 1997-2016.

Francisco J Huera Huarte, *Visiting Associate in Aerospace*
M.E., Universitat Politecniva Catalunya, 2003; Ph.D, Imperail College, London, 2006. Caltech, 2014; 2015.

Mark S Humayun, *Visiting Associate in Medical Engineering*
B.S., Georgetown University, 1984; M.D., Duke University, 1989; Ph.D., University of North Carolina, 1992. Caltech, 2014-16.

Hui-Ming Hung, *Visiting Associate in Environmental Science and Engineering*
B.S., National Taiwan University, 1993; M.S., 1995; Ph.D., California Institute of Technology, 2000. Caltech, 2014.

Melany L Hunt, Ph.D., *Dotty and Dick Hayman Professor of Mechanical Engineering*
B.S., University of Minnesota, 1983; M.S., University of California, 1985; Ph.D., 1987. Assistant Professor, Caltech, 1988-95; Associate Professor, 1995-2001; Professor, 2001-2011; Kenan Professor, 2012-13; Hayman Professor, 2013-; Executive Officer, 2002-2007; Vice Provost, 2007-14.

Christopher A Hunter, Ph.D., *Assistant Professor of English*
B.A., Harvard University, 2002; M.A.,

University of Pennsylvania, 2004; Ph.D., 2009. Caltech, 2010-.

Rene Hurlemann, *Visiting Associate in Psychology*
M.D., University of Bonn Medical School, 2001; M.Sc., Universities of Maastricht and Florence, 2006; Ph.D., Maastricht University, 2007. Caltech, 2013-15.

Sonjong Hwang, *Lecturer in Chemistry*
B.S., Sogang University (Korea), 1987; Ph.D., Iowa State University, 1994. Caltech, 2001-09, 2010, 2012, 2015.

Joshua Hyman, *Lecturer in Computing and Mathematical Sciences*
B.S., University of California, Los Angeles, 2005; M.S., 2008; Ph.D., 2009. Caltech, 2012, 2013, 2014; 2015.

Andrew P Ingersoll, Ph.D., *Professor of Planetary Science*
B.A., Amherst College, 1960; A.M., Harvard University, 1961; Ph.D., 1966. Assistant Professor, Caltech, 1966-71; Associate Professor, 1971-76; Professor, 1976-2003; 2011-; Anthony Professor, 2003-11. Executive Officer for Planetary Science, 1987-94.

Christos A Ioannou, *Visiting Associate in Economics*
B.S., University of Arizona, 2001; Ph.D., University of Minnesota, 2009. Caltech, 2015.

Rustem F Ismagilov, Ph.D., *Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering; Director of the Jacobs Institute for Molecular Engineering for Medicine*
B.S., Higher Chemical College of the Russian Academy of Sciences, 1994; Ph.D., University of Wisconsin, Madison, 1998. Miles Professor, Caltech, 2011-13; Bowles Professor, 2013-; Director, Jacobs Institute, 2013-.

Mikinori Ito, *Visiting Associate in Applied Physics and Materials Science*
B.S., Toyohoshi University of Technology, 2003; M.S., 2005; Ph.D, 2008. Caltech, 2014-16.

Wilfred D (Bill) Iwan, Ph.D., *Professor of Applied Mechanics, Emeritus*
B.S., Caltech, 1957; M.S., 1958; Ph.D., 1961. Assistant Professor, 1964-67; Associate Professor, 1967-72; Professor, 1972-2004; Professor Emeritus, 2004-. Executive Officer for Civil Engineering and Applied Mechanics, 1980-86.

Jennifer M Jackson, Ph.D., *Professor of Mineral Physics*
B.S., University of Illinois (Urbana-Champaign), 1999; M.S., University of Notre Dame, 2000; Ph.D., University of Illinois, 2005. Assistant Professor of Geophysics, Caltech, 2007-09; Assistant Professor of Mineral Physics, 2009-12; Professor, 2012-.

Jennifer A Jahner, Ph.D., *Assistant Professor of English*
B.A., Western Washington University, 1998; M.A., University of Colorado at Boulder, 2005, Ph.D., University of Pennsylvania, 2012. Caltech, 2012-.

Gregory S Jefferis, Ph.D., *Moore Distinguished Scholar*
B.A., University of Cambridge, 1998; Ph.D., Stanford University, 2004. Caltech, 2015.

Paul C Jennings, Ph.D., *Professor of Civil Engineering and Applied Mechanics, Emeritus*
B.S., Colorado State University, 1958; M.S., Caltech, 1960; Ph.D., 1963. Research Fellow in Civil Engineering, 1965; Assistant Professor of Applied Mechanics, 1966-68; Associate Professor, 1968-72; Professor, 1972-77; Professor of Civil Engineering and Applied Mechanics, 1977-2002; 2004-2007. Professor Emeritus, 2002-04; 2007-. Executive Officer for Civil Engineering and Applied Mechanics, 1975-80; Chairman, Division of Engineering and Applied Science, 1985-89; Vice President and Provost, 1989-95; Acting Vice President for Business and Finance, 1995; 1998-99; Provost, 2004-07.

Grant J Jensen, Ph.D., *Professor of Biophysics and Biology; Investigator, Howard Hughes Medical Institute*
B.S., Brigham Young University, 1994; Ph.D., Stanford University, 1999. Assistant Professor, Caltech, 2002-2008; Associate Professor, 2008-10; Professor, 2010-; Investigator, 2008-.

Sanggeun Jeon, *Visiting Associate in Electrical Engineering*
B.S., Seoul National University, 1997; M.S., California Institute of Technology, 2004; Ph.D., 2006. Caltech, 2015-16.

Bing Jiang, *Visiting Associate in Physics*
B.S., Nanjing University, 2003; Ph.D., 2009. Caltech, 2015-16.

Chenyang (Sunny) Jiang, *Visiting Associate in Environmental Science and Engineering*
M.S., University of South Florida, 1993; Ph.D, 1996. Caltech, 2013-15.

Jian Jin, *Visiting Associate in Chemistry*
B.S., Sichuan University, 1982, M.S., 1984; Ph.D., Texas A & M University, 1993. Caltech, 2012-15.

Jiaqi (Lawrence) Jin, Ph.D., *Assistant Professor of Finance*
B.S., Tsinghua University China, 2005; M.S., California Institute of Technology, 2006; Ph.D., Yale University, 2015. Caltech, 2015-.

Hope A Johnson, *Visiting Assoicate in Geobiology*
B.S., Cornell University, 1993; M.S., Stanford University, 1994, Ph.D., 2001. Caltech, 2015.

William L Johnson, Ph.D., *Ruben F. and Donna Mettler Professor of Engineering and Applied Science*
B.A., Hamilton College, 1970; Ph.D., Caltech, 1975. Assistant Professor of Materials Science, 1977-80; Associate Professor, 1980-84; Professor, 1984-89; Mettler Professor, 1989-.

Lucile M Jones, *Visiting Associate in Geophysics*
A.B., Brown University, 1976; Ph.D., Massachusetts Institute of Technology, 1981. Research Associate, U.S. Geological Survey, 1984-. Caltech, 1984-2015.

Catherine Jurca, Ph.D., *Professor of English; Executive Officer for the Humanities*
B.A., University of California, 1987; M.A., Johns Hopkins University, 1992; Ph.D., 1995. Instructor, Caltech, 1995; Assistant Professor, 1995-2001; Associate Professor of Literature, 2001-04; Associate Professor of English, 2004-10; Professor, 2010-; Master of Student Houses, 2002-09; Executive Officer, 2014-.

Hiroo Kanamori, Ph.D., *John E. and Hazel S. Smits Professor of Geophysics, Emeritus*
B.S., University of Tokyo, 1959; M.S., 1961; Ph.D., 1964. Research Fellow, Caltech, 1965-66; Professor, 1972-89; Smits Professor, 1989-2005; Smits Professor Emeritus, 2005-. Director, Seismological Laboratory, 1990-98.

Anton N Kapustin, Ph.D., *Earle C. Anthony Professor of Theoretical Physics and Mathematics*
M.S., Moscow State University, 1993; Ph.D., Caltech, 1997. Assistant Professor, 2001-04; Associate Professor, 2004-10; Professor, 2010-12; Earle C. Anthony Professor, 2012-.

Emil P Kartalov, *Visiting Associate in Physics*
B.S., Caltech, 1998; M.S., 2004; Ph.D., 2004. Assistant Professor, University of Southern California, 2007-. Visiting Associate, Caltech, 2008-16.

Mansi Kasliwal, Ph.D., *Assistant Professor of Astronomy*
B.S., Cornell University, 2004; M.S., California Institute of Technology, 2007; Ph.D., 2011. Caltech, 2015-.

Jonathan N Katz, Ph.D., *Kay Sugahara Professor of Social Sciences and Statistics*
S.B., Massachusetts Institute of Technology, 1990; M.A., University of California (San Diego), 1992; Ph.D., 1995. Assistant Professor, Caltech, 1995-98; Associate Professor, 1998; 1999-2003; Professor, 2003-11; Sugahara Professor, 2012-; Executive Officer for the Social Sciences, 2007; Director, Linde Institute, 2013-14; Division Chair, 2007-14.

Nets H Katz, Ph.D., *Professor of Mathematics*
B.A., Rice University, 1990; Ph.D., University of Pennsylvania, 1993. Caltech, 2013-.

Sarah M Keating, *Visiting Associate in Computing and Mathematical Sciences*
B.S., Open University, 1996; M.S., University College London, 1998; Ph.D., 2002. Caltech, 2013-16.

Alexander Kechris, Ph.D., D.h.c., *Professor of Mathematics*
M.S., National Technical University, Athens, 1969; Ph.D., University of California, Los Angeles, 1972; D.h.c., University of Athens. Assistant Professor, Caltech, 1974-76; Associate Professor, 1976-81; Professor, 1981-. Executive Officer for Mathematics, 1994-97.

Daniel (Dan) Kennedy, *Visiting Associate in Neuroscience*
B.S., Binghamton University, 2002; Ph.D., University of California San Diego, 2007. Caltech, 2013-14; 2015.

Mary B Kennedy, Ph.D., *The Allen and Lenabelle Davis Professor of Biology*
B.S., St. Mary's College, 1969; Ph.D., Johns Hopkins University, 1975. Assistant Professor, Caltech, 1981-84; Associate Professor, 1984-92; Professor, 1992-2002; Davis Professor, 2002-.

Daniel J Kevles, Ph.D., *J. O. and Juliette Koepfli Professor of the Humanities, Emeritus*
A.B., Princeton University, 1960; Ph.D., 1964. Assistant Professor of History, Caltech, 1964-68; Associate Professor, 1968-78; Professor, 1978-86; Koepfli Professor of the Humanities, 1986-2001; Koepfli Professor Emeritus, 2001-. Executive Officer for the Humanities, 1978-81.

D R (Rod) Kiewiet, Ph.D., *Professor of Political Science*
B.A., University of Iowa, 1974; Ph.D., Yale University, 1980. Assistant Professor, Caltech, 1979-82; Associate Professor, 1982-89; Professor, 1989-. Dean of Students, 1992-96; Dean of Graduate Studies, 2000-02; Dean of Undergraduate Students, 2011-14.

Hyoung Ihl Kim, *Visiting Associate in Biology and Biological Engineering*
B.S., Jeunbuk University, 1979; M.S., 1982; Ph.D., 1987. Caltech, 2014-15.

Keunbae Kim, *Visiting Associate in Applied Physics and Materials Science*
B.S., Inha University, 1988; M.S., 1993; Ph.D., Chungnam National University, 2005. Caltech, 2014-15.

Soonhyun Kim, *Visiting Associate in Enviornmental Science and Engineering*
B.S., Ajou University, 2000; Ph.D., Postech, 2005. Caltech, 2015-16.

H. J Kimble, Ph.D., D.Sc.h.c., *William L. Valentine Professor and Professor of Physics*
B.S., Abilene Christian University, 1971;

M.S., University of Rochester, 1973; Ph.D., 1978; D.Sc.h.c., Niels Borhr Institute, University of Copenhagen. Professor, Caltech, 1989-; Valentine Professor, 1997-.

Evan N Kirby, Ph.D., *Assistant Professor of Astronomy*
B.S., Stanford University, 2004; M.S., University of California, Santa Cruz, 2006; Ph.D., 2009. Caltech, 2014-.

Joseph (Joe) Kirschvink, Ph.D., *Nico and Marilyn Van Wingen Professor of Geobiology*
B.S., M.S., Caltech, 1975; M.A., Princeton University, 1978; Ph.D., 1979. Assistant Professor, Caltech, 1981-87; Associate Professor, 1987-92; Professor, 1992-2004; Van Wingen Professor, 2004-.

Yusuke Kita, *Visiting Associate in Chemistry*
B.S., Osaku Univeristy, M.D., 2006; Ph.D., 2010. Caltech, 2014-15.

Alexei Kitaev, Ph.D., *Ronald and Maxine Linde Professor of Theoretical Physics and Mathematics*
Dipl., Moscow Institute of Physics and Technology, 1986; Ph.D., Landau Institute for Theoretical Physics, 1989. Visiting Associate, Caltech, 1998-99; Lecturer, 1998-99; Senior Research Associate, 2001-02; Professor, 2002-13; Linde Professor, 2013-.

Wolfgang G Knauss, Ph.D., *Theodore von Karman Professor of Aeronautics and Applied Mechanics, Emeritus*
B.S., Caltech, 1958; M.S., 1959; Ph.D., 1963. Research Fellow in Aeronautics, 1963-65; Assistant Professor, 1965-69; Associate Professor, 1969-78; Professor, 1978-82; Professor of Aeronautics and Applied Mechanics, 1982-2001; von Karman Professor, 2001-2004; von Karman Professor Emeritus, 2004-.

Heather A Knutson, Ph.D., *Assistant Professor of Planetary Science*
B.Sc., Johns Hopkins University, 2004; A.M., Harvard University, 2006; Ph.D., 2009. Visiting Associate, Caltech, 2010-11; Assistant Professor, 2011-.

Dennis M Kochmann, Dr.-Ing, *Assistant Professor of Aerospace*
Dipl.-Ing, Ruhr-University, Bochum, 2006; M.S., University of Wisconsin-Madision, 2006; Dr.-Ing, Ruhr-University, Bochum, 2009. Caltech, 2011-.

Jin Koda, *Visiting Associate in Physics*
Ph.D., University of Tokyo, 2002. Caltech, 2015.

Monica D Kohler, *Senior Research Fellow in Mechanical and Civil Engineering; Lecturer in Mechanical and Civil Engineering*
A.B., Harvard University, 1988; Ph.D., Caltech, 1995. Assistant Research Engineer, University of California (Los Angeles), 1998-. Visiting Associate, Caltech, 2007-11; Lecturer, 2009, 2012, 2013; Research Assistant Professor, 2011-17.

Masakazu (Mark) Konishi, Ph.D., *Bing Professor of Behavioral Biology, Emeritus*
B.S., Hokkaido University (Japan), 1956; M.S., 1958; Ph.D., University of California, 1963. Professor of Biology, Caltech, 1975-80; Bing Professor, 1980-13; Bing Professor, Emeritus, 2013-. Executive Officer for Biology, 1977-80.

Diana L Kormos-Buchwald, Ph.D., *Professor of History*
B.Sc., Technion-Israel Institute of Technology, 1981; M.Sc., Tel Aviv University, 1983; A.M., Harvard University, 1985; Ph.D., 1990. Instructor, Caltech, 1989-90; Assistant Professor, 1990-96; Associate Professor, 1996-2005; Professor, 2005-.

Julia A Kornfield, Ph.D., *Professor of Chemical Engineering*
B.S., Caltech, 1983; M.S., 1984; Ph.D., Stanford University, 1988. Assistant Professor, Caltech, 1990-95; Associate Professor, 1995-2001; Professor, 2001-.

David A Kosower, Ph.D., *Moore Distinguished Scholar*
A.B., Harvard College, 1982; Ph.D., Harvard University, 1986. Caltech, 2015.

Victoria Kostina, Ph.D., *Assistant Professor of Electrical Engineering*
B.S., Moscow Institute of Physics and Technology, 2004; M.S., University of Ottawa, 2006; Ph.D., Princeton University, 2013. Caltech, 2014-.

Petros D Koumoutsakos, *Clark B. Millikan Visiting Professor in Aerospace*
Dipl., National Technical University of Athens, 1986; B.S., University of Michigan, 1987; M.S., Caltech, 1988; Ph.D., 1992. Director, Institute of Scientific Computing, ETH Zurich. 2003-. Research Fellow, Caltech, 1992-1994; Millikan Visiting Professor, 2009-10. Caltech, 2011-13; 2014; 2015.

J. M (Morgan) Kousser, Ph.D., *William R. Kenan, Jr., Professor of History and Social Science*
A.B., Princeton University, 1965; M.Phil., Yale University, 1968; Ph.D., 1971. Instructor in History, Caltech, 1969-71; Assistant Professor, 1971-74; Associate Professor, 1974-79; Professor, 1979-80; Professor of History and Social Science, 1980-2013; Kenan Professor, 2013-.

Carl A Koval, *Faculty Associate in Chemistry, JCAP*
B.S., Juniata College, 1994; Ph.D., California Institute of Technology, 1979. Caltech, 2013-.

Anne J Kox, *Visiting Associate in History*
M.S., University of Amsterdam, 1972; Ph.D.,

1976. Pieter Zeeman Professor, 1998-. Visiting Professor, Caltech, 2003; Visiting Associate, 2005-16.

David Kremers, *Visiting Associate in Aerospace*
B.F.A., Pepperdine University, 1985. Caltech, 2014-15.

Mariska E Kret, *Visiting Associate in Psychology*
M.S., Leiden University, 2006; M.S., 2007; Ph.D., Tilburg University, 2011. Caltech, 2015.

Swaminathan (Swami) Krishnan, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Indian Institute of Technology, 1992; M.S., Rice University, 1994; Ph.D., Caltech, 2003. Assistant Professor of Civil Engineering, 2006-07; Assistant Professor of Civil Engineering and Geophysics, 2007-10; Assistant Professor of Structural Engineering and Geophysics, 2010-13. Visiting Associate in Mechanical and Civil Engineering, 2013-15.

Clifford Kubiak, *Visiting Associate in Chemistry, JCAP*
Sc.B, Brown University, 1975; Ph.D., University of Rochester, 1980. Professor and Chair in Chemistry University of California, San Diego, 1998-. Caltech, 2012-15.

Shrinivas R (Shri) Kulkarni, Ph.D., D.h.c., John D. and Catherine T. MacArthur
Professor of Astronomy and Planetary Science; Director, Caltech Optical Observatories
M.S., Indian Institute of Technology, 1978; Ph.D., University of California, 1983; D.h.c., Radboud University. Millikan Research Fellow in Radio Astronomy, Caltech, 1985-87; Assistant Professor of Astronomy, 1987-90; Associate Professor, 1990-92; Professor, 1992-96; Professor of Astronomy and Planetary Science, 1996-2001; MacArthur Professor, 2001-. Executive Officer for Astronomy, 1997-2000. Director, 2006-.

Akiko Kumagai, *Research Professor of Biology*
B.S., Kyoto University (Japan), 1979; Ph.D., 1986. Senior Research Fellow, Caltech, 1989-95; Senior Research Associate, 1996-2014; Research Professor, 2014-.

Rahul Kumar, *Lecturer in Computing and Mathematical Sciences*
B.S., Brigham Young University, Utah, 2002; M.S., 2004; Ph.D., 2003; Caltech, 2015.

Jenijoy La Belle, Ph.D., *Professor of English, Emeritus*
B.A., University of Washington, 1965; Ph.D., University of California (San Diego), 1969. Assistant Professor of English, Caltech, 1969-76; Associate Professor, 1977-80; Associate Professor of Literature, 1980-88; Professor of Literature, 1988-2004; Professor of English, 2004-2007; Professor Emeritus, 2007-.

Jay A Labinger, *Faculty Associate in Chemistry*
B.S., Harvey Mudd College, 1968; Ph.D., Harvard University, 1974. Caltech, 1988-1996; Faculty Associate, 2006-; Lecturer, 2008-11.

Farshad Lahouti, *Visiting Professor in Electrical Engineering*
B.S., University of Tehran, 1996; Ph.D., University of Waterloo, 2002. Caltech, 2013-15.

Michael P Lamb, Ph.D., *Professor of Geology*
B.S., University of Minnesota, 2001; M.S., University of Washington, 2004; Ph.D., University of California, Berkeley, 2008. Assistant Professor, Caltech, 2009-14; Professor, 2014-.

Nadia Lapusta, Ph.D., *Professor of Mechanical Engineering and Geophysics*
Dipl., Kiev State University, 1994; M.S., Harvard University, 1996; Ph.D., 2001. Assistant Professor of Mechanical Engineering, Caltech, 2002-03; Assistant Professor of Mechanical Engineering and Geophysics, 2003-08; Associate Professor, 2008-10; Professor, 2010-.

Eugene Lavretsky, *Lecturer in Computing and Mathematical Sciences*
M.S., Saratov State University (Russia), 1983; Ph.D., Claremont Graduate University, 2000. Caltech, 2006-14; 2015.

Jared R Leadbetter, Ph.D., *Professor of Environmental Microbiology*
B.S., Goucher College, 1991; Ph.D., Michigan State University, 1997. Assistant Professor, Caltech, 2000-06; Associate Professor, 2006-10; Professor, 2010-.

John O Ledyard, Ph.D., D.Lit.h.c., *Allen and Lenabelle Davis Professor of Economics and Social Sciences*
A.B., Wabash College, 1963; M.S., Purdue University, 1965; Ph.D., 1967; D.Lit.h.c., Purdue University. Professor, Caltech, 1985-2002; Davis Professor, 2002-. Executive Officer for the Social Sciences, 1989-92; Chair, Division of the Humanities and Social Sciences, 1992-2002.

Brian Lee, *Visiting Associate in Biology and Biological Engineering*
B.S., University of Southern California, 1999; Ph.D., Caltech, 2006; M.D., University of Southern California, 2008. Caltech, 2013-16.

Hansuek Lee, *Visiting Associate in Applied Physics and Materials Science*
B.S, Seoul National University, 2001; M.S., 2004; Ph.D, 2008. Caltech, 2013-15.

Hyosang Lee, *Research Assistant Professor of Biology and Biological Engineering*
B.Sc, Kyungppk National University, 1995; M.Sc., Pohang University of Science &

Technology, 1997; Ph.D., Johns Hopkins University, 2006. Caltech, 2013-16.

Richard Lee, *Visiting Associate in Physics*
Ph.D., Lancaster University, 1994. Senior Member, Technical Staff, Jet Propulsion Laboratory, 2007-. Caltech, 2007-15.

Tai K Lee, *Visiting Associate in Environmental Science and Engineering*
B.S., Yonsei University, 1977; M.S., 1979; Ph.D., University of New Mexico, 1987. Caltech, 2013-16.

Dennis Lehmkuhl, *Research Assistant Professor of History and Philosophy of Science*
MSc., Imperial College London, 2003; M.A., Hamburg University, 2006; DPhil., Oxford University (Oriel College), 2009. Visiting Associate, Caltech, 2010, 2012, 2015-18.

Anthony Leonard, Ph.D., *Theodore von Karman Professor of Aeronautics, Emeritus*
B.S., Caltech, 1959; M.S., Stanford University, 1960; Ph.D., 1963. Professor, Caltech, 1985-2000; von Karman Professor, 2000-2005; von Karman Professor Emeritus, 2005-.

Henry A Lester, Ph.D., *Bren Professor of Biology*
A.B., Harvard College, 1966; Ph.D., Rockefeller University, 1971. Assistant Professor, Caltech, 1973-76; Associate Professor, 1976-83; Professor, 1983-2000; Bren Professor, 2000-; Executive Officer, 2010-13.

Carmel Levitan, *Visiting Associate in Biology*
B.A., Stanford University, 2001; Ph.D., University of California (San Francisco & Berkely), 2007. Caltech, 2009-15.

Nathan S (Nate) Lewis, Ph.D., *George L. Argyros Professor and Professor of Chemistry*
B.S., Caltech, 1977; M.S., 1977; Ph.D., Massachusetts Institute of Technology, 1981. Associate Professor, Caltech, 1988-91; Professor, 1991-; Argyros Professor, 2002-.

Han Li, *Visiting Associate in Applied Physics and Materials Science*
B.S., Wuhan University of Technology, 2001; M.S., 2005; Ph.D., 2009. Caltech, 2013-15.

Hui Li, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Qing Dao Polytechnic University, 1988; M.S., Harbin Institute of Technology, 1991; Ph.D., 1994. Caltech, 2015.

Jiangang Li, *Visiting Associate in Computing and Mathematical Sciences*
B.S., Xi'an University of Architecture and Technology, 1999; M.S., 2002; Ph.D., 2005. Caltech, 2015-16.

Qin Li, von Karman *Instructor in Computing and Mathematical Sciences*
B.S., Tsinghua University, 2009; Ph.D., University of Wisconsin-Madison, 2013. Caltech, 2013-15.

Kenneth G Libbrecht, Ph.D., *Professor of Physics*
B.S., Caltech, 1980; Ph.D., Princeton University, 1984. Visiting Associate in Solar Astronomy, Caltech, 1984; Assistant Professor of Astrophysics, 1984-89; Associate Professor, 1989-95; Professor of Physics, 1995-. Executive Officer, 1997-13.

Daniel Lidar, *Visiting Associate in Theoretical Physics*
Ph.D., Hebrew University, 1997. Associate Professor, University of Southern California, 2005-. Caltech, 2008-2015.

Ron Y Lifshitz, *Visiting Associate in Physics*
B.Sc., Hebrew University of Jerusalem, 1990; Ph.D., Cornell University, 1995. Associate Professor, Tel Aviv University, 2006-. Research Fellow, Caltech, 1995-98; Senior Research Fellow, 1998-99; Visiting Associate, 2001; 2003; 2006-07; 2009; 2011-15.

Katrina A Ligett, Ph.D., *Assistant Professor of Computer Science and Economics*
B.S., Brown University, 2004; M.S., Carnegie Mellon University, 2007; Ph.D., 2009. Caltech, 2011-.

Alice Lin, *Lecturer in Business, Economics, and Management*
B.S., California Institute of Technology, 2001; Ph.D., 2012. Caltech, 2012-14; 2015.

Fan-Chi Lin, *Visiting Associate in Geophysics*
B.S., National Tsing Hua University, 2000; M.S., Drexel University, 2005; Ph.D., University of Colorado, Boulder, 2009. Caltech, 2015-17.

Dariusz C (Darek) Lis, *Visiting Associate in Physics*
Ph.D., University of Massachusetts (Amherst), 1989. Research Fellow, Caltech, 1989-92; Senior Research Fellow, 1992-98; Senior Research Associate, 1998-2015; Visiting Associate, 2015-16.

E J (John) List, Ph.D., *Professor of Environmental Engineering Science, Emeritus*
B.E., University of Auckland, 1961; M.E., 1962; Ph.D., Caltech, 1965. Research Fellow, 1965-66; Assistant Professor, 1969-72; Associate Professor, 1972-78; Professor, 1978-97; Professor Emeritus, 1997-. Executive Officer for Environmental Science, 1980-85.

Charles Y Liu, *Visiting Associate in Biology and Biological Engineering*
B.S.E., University of Michigan (Ann Arbor), 1987; Ph.D., Rice University, 1993; M.D., Yale University School of Medicine, 1996. Resident Physician, University of Southern California, Keck School of Medicine, 1996-. Caltech, 2002-11; 2014-15.

Yang Liu, *Visiting Associate in Geochemistry*
B.S., Chengdu University of Technology, 1995; M.S., University of Michigan, 1998; Ph.D., University of Michigan, 2003. Lecturer, 2015; Caltech, 2013-16.

Yi Liu, *Taussky-Todd Instructor in Mathematics*
B.S., Peking University, 2006; Ph.D., University of California, Berkeley, 2012. Caltech, 2012-15.

Alexis Livanos, *Faculty Associate in Aerospace*
B.S., California Institute of Technology, 1970; M.S., 1972; Ph.D., 1975. Caltech, 2013- .

Carlos Lois, *Research Professor*
M.D., University of Valencia, 1991; Ph.D., Rockefeller University, 1995. Caltech, Visiting Associate, 2014-15; Research Professor 2015-.

Santiago V Lombeyda, *Lecturer in Biology and Biological Engineering*
B.S., Texas Christian University, 1995; M.S., Drexel University, 1998. Caltech, 2013, 2014, 2015.

Sylvia A Lopez-Vetrone, *Visiting Associate in Biology and Biological Engineering*
B.A., Whittier College, 1999; Ph.D., University of California, Los Angeles, 2008. Caltech, 2014-15.

Gary A Lorden, Ph.D., *Professor of Mathematics, Emeritus*
B.S., Caltech, 1962; Ph.D., Cornell University, 1966. Assistant Professor, Caltech, 1968-71; Associate Professor, 1971-77; Professor, 1977-2009; Professor Emeritus, 2009-. Dean of Students, 1984-88; Vice President for Student Affairs, 1989-98; Acting Vice President, 2002; Executive Officer for Mathematics, 2003-2006.

Luiz Lourenco, *Visiting Associate in Aerospace*
D.Eng., Oporto University, 1984; D.Sc., Brussels University, 1982. Caltech, 2011-15.

Steven H Low, Ph.D., *Professor of Computer Science and Electrical Engineering*
B.S., Cornell University, 1987; M.S., University of California, 1989; Ph.D., 1992. Associate Professor, Caltech, 2000-06; Professor, 2006-.

Xilin Lu, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Chongqing University, 2003; M.S., 2005; Ph.D., Tongji University, 2009. Caltech, 2012; 2014-15.

W A Luxemburg, Ph.D., *Professor of Mathematics, Emeritus*
B.A., University of Leiden, 1950; M.A., 1953; Ph.D., Delft Institute of Technology, 1955. Assistant Professor, Caltech, 1958-60; Associate Professor, 1960-62; Professor, 1962-2000; Professor Emeritus, 2000-. Executive Officer for Mathematics, 1970-85.

Douglas G (Doug) MacMartin, *Research Professor of Computing and Mathematical Sciences; Lecturer in Computing and Mathematical Sciences*
B.A.Sc., University of Toronto, 1987; S.M., Massachusetts Institute of Technology, 1990; Ph.D., 1992. Visiting Associate, Caltech, 2000-02; Lecturer, 2001; 2004; 2005; 2009-2014. Senior Research Fellow, 2002-08; Research Professor, 2008-.

Walid Majid, *Visiting Associate in Experimental Astrophysics*
B.S., Swarthmore College, 1986; M.S., University of Illinois, Urbana, 1987; Ph.D., 1993. Caltech, 2015-16.

Nikolai Makarov, Ph.D., *Richard Merkin Distinguished Professor of Mathematics*
B.A., Leningrad University, 1982; Ph.D., LOMI Mathematics Institute (Leningrad), 1986. Visiting Professor, Caltech, 1991; Professor, 1991-13; Merkin Professor, 2013-.

Maciej M Malicki, *Visiting Associate in Mathematics*
M.A., Warsaw University, 2000; Ph.D., University of Illinois, 2007. Caltech, 2015.

H M (Chinthaka) Mallikarachchi, *Visiting Associate in Aerospace*
B.S., University of Moratuwa, Sri Lanka, 2005; Ph.D., University of Cambridge, 2011. Caltech, 2013; 2015.

Oscar Mandel, Ph.D., *Professor of Literature, Emeritus*
B.A., New York University, 1947; M.A., Columbia University, 1948; Ph.D., Ohio State University, 1951. Visiting Associate Professor of English, Caltech, 1961-62; Associate Professor, 1962-68; Professor, 1968-80; Professor of Literature, 1980-2003; Professor Emeritus, 2003-.

Gideon Manning, Ph.D., *Assistant Professor of Philosophy*
A.B., Harvard University, 1997; Ph.D., University of Chicago, 2006. Caltech, 2007-.

Elena Mantovan, Ph.D., *Professor of Mathematics Laurea,*
University of Padova, 1995; M.A., Harvard University, 1998; Ph.D., 2002. Assistant Professor, Caltech, 2005-10; Associate Professor, 2010; Professor, 2010-.

Sandra E Marbut, *Head Coach of Women's Basketball and Physical Education Instructor*
B.A., Sheldon Jackson College, 1991; M.A., Concordia University, 2011. Caltech, 2003-.

Matilde Marcolli, Ph.D., *Professor of Mathematics Laurea,*
University Degli Studi, 1993; M.Sc., University of Chicago, 1994; Ph.D., 1997. Caltech, 2008-

Rudolph A (Rudy) Marcus, Ph.D., D.Sc.h.c., Fil.Dr.h.c., D.h.c., Nobel Laureate., *John G. Kirkwood and Arthur A. Noyes Professor of Chemistry*
B.Sc., McGill University, 1943; Ph.D., 1946; D.Sc.h.c., University of Chicago; McGill University; Polytechnic University; University of Oxford; University of New Brunswick; Queen's University; University of North Carolina (Chapel Hill); University of Ilinois; Technion-Israel Institute of Technology; Universidad Politecnica de Valencia; University of Waterloo; Fil.Dr.h.c., Gothenburg University; D.h.c., Yokohama National University; Northwestern University. Noyes Professor, Caltech, 1978-2012; Kirkwood-Noyes Professor, 2013-.

Vladimir Markovic, Ph.D., *John D. MacArthur Professor of Mathematics*
B.Sc., University of Belgrade, 1995; Ph.D., 1998. Professor, Caltech, 2011-13; MacArthur Professor, 2013-.

Shirley A Marneus, *Lecturer in Theater Arts, Emeritus*
B.A., San Jose State College, 1959; M.A., State University of Iowa, 1962. Lecturer in Literature, Caltech, 1999-2005; Lecturer in English, 2005-07; Lecturer in Theater Arts, 1999-2008; Lecturer in Theater Arts, Emeritus, 2008.

Richard E Marsh, *Senior Research Associate in Chemistry, Emeritus*
B.S., Caltech, 1943; Ph.D., University of California (Los Angeles), 1950. Research Fellow, Caltech, 1950-55; Senior Research Fellow, 1955-73; Research Associate, 1973-81; Senior Research Associate, 1981-90; Senior Research Associate Emeritus, 1990-.

Alain J Martin, Ing., *Professor of Computer Science*
B.S., University of Marseille, 1965; Ing., Polytechnic Institute (Grenoble), 1969. Visiting Assistant Professor, Caltech, 1981-83; Visiting Associate Professor, 1983; Associate Professor, 1983-86; Professor, 1986-. Executive Officer, 1994-97.

Christopher Martin, Ph.D., *Professor of Physics*
B.A., Oberlin College, 1978; Ph.D., University of California, 1986. Caltech, 1993-.

Christoph Marx, *Harry Bateman Research Instrustor in Mathematics*
B.S., University of Vienna, 2006; M.S., University of California, Irvine, 2008; Ph.D., 2012. Caltech, 2012-15.

Peter V Mason, *Visiting Associate in Physics*
B.S., Caltech, 1951; M.S., 1952; Ph.D., 1962. Technical Staff, Retired, Jet Propulsion Laboratory, 1997-. Assistant Professor, Caltech, 1962-66; Visiting Associate, 1997-2015.

Georgios Matheou, *Visiting Associate in Aerospace*
Dipl., National Technical University of Athens, 2002; Ph.D., California Institute of Technology, 2008. Caltech, 2013-15.

Larry H Matthies, *Lecturer in Mechanical and Civil Engineering*
B.S., University of Regina, 1979; M.Math., University of Waterloo, 1981; Ph.D., Carnegie Mellon University, 1989. Caltech, 2011; 2013; 2015.

Dimitri P Mawet, Ph.D., *Associate Professor of Astronomy; Jet Propulsion Laboratory Research Scientist*
Dipl., University of Liege, 2002; M.Phil., 2004; Ph.D., 2006. Caltech, 2015-. Jet Propulsion Laboratory Research Scientist, 2015-.

Stephen L (Steve) Mayo, Ph.D., *Bren Professor of Biology and Chemistry; William K. Bowes Jr. Leadership Chair, Division of Biology and Biological Engineering*
B.S., Pennsylvania State University, 1983; Ph.D., Caltech, 1987. Senior Research Fellow, 1991-92; Assistant Professor, 1992-98; Associate Professor, 1998-2003; Professor, 2003-07; Bren Professor, 2007-. Assistant Investigator, 1994-2000; Associate Investigator, 2000-05; Investigator, 2005-07; Executive Officer for Biochemistry and Molecular Biophysics, 2004-07; Vice Provost, 2007-10; Division Chair, 2010-12; Bowes Jr. Leadership Chair, 2012-.

Sarkis Mazmanian, Ph.D., *Luis B. and Nelly Soux Professor of Microbiology*
B.S., University of California (Los Angeles), 1995; Ph.D., 2002. Assistant Professor, Caltech, 2006-12; Professor, 2012-14; Soux Professor, 2014-.

Edward J McCaffery, *Visiting Professor of Law*
B.A., Yale University, 1980; J.D., Harvard Law School, 1985. Associate Professor, University of Southern California, 1991-. Visiting Associate Professor, Caltech, 1996-97; Visiting Professor, 1997; 2008-15; Visiting Associate, 2008-09.

Daniel McCleese, *Visiting Associate in Planetary Science*
B.S., Antioch College, 1972; D.Phil, University of Oxford, 1976. Chief Scientist, Jet Propulsion Laboratory, 1994-. Caltech, 2002-15.

Robert J McEliece, Ph.D., *Allen E. Puckett Professor and Professor of Electrical Engineering, Emeritus*
B.S., Caltech, 1964; Ph.D., 1967. Professor, 1982-2007; Puckett Professor, 1997-2007; Pucket Professor and Professor, Emeritus, 2007-. Executive Officer for Electrical Engineering, 1990-99.

Beverley J McKeon, Ph.D., *Professor of Aeronautics; Associate Director, Graduate Aerospace Laboratories*
B.A., University of Cambridge, 1995; M.Eng.,1996; M.A. (Mechanical and Aerospace Engineering); M.A. (Engineering), Princeton University, 1999; Ph.D., 2003. Assistant Professor, Caltech, 2006-11; Professor, 2011-; Associate Director, 2012-.

Basil V (Vincent) McKoy, Ph.D., *Professor of Theoretical Chemistry*
B.S., Nova Scotia Technical University, 1960; Ph.D., Yale University, 1964. Noyes Research Instructor in Chemistry, Caltech, 1964-66; Assistant Professor of Theoretical Chemistry, 1967-69; Associate Professor, 1969-75; Professor, 1975-.

Aaron M Mead, *Lecturer in Philosophy*
B.S., Stanford University, 1994; M.S., 1995; M.Div., Fuller Theological Seminary, 2005; M.A., California State University Los Angeles, 2007; M.A., University of California Los Angeles, 2009; Ph.D., 2015. Caltech, 2015.

Carver Mead, Ph.D., D.Sc.h.c., D.h.c., *Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus*
B.S., Caltech, 1956; M.S., 1957; Ph.D., 1960; D.Sc.h.c., University of Lund (Sweden); D.h.c., University of Southern California. Instructor in Electrical Engineering, Caltech, 1958-59; Assistant Professor, 1959-62; Associate Professor, 1962-67; Professor, 1967-77; Professor of Computer Science and Electrical Engineering, 1977-80; Moore Professor of Computer Science, 1980-92; Moore Professor of Engineering and Applied Science, 1992-99; Moore Professor Emeritus, 1999-.

Barry Megdal, *Lecturer in Electrical Engineering*
B.S., Caltech, 1977; M.S., 1978; Ph.D., 1983. Lecturer, 1992-2015.

David L Meier, *Visiting Associate in Astronomy*
Ph.D., University of Texas, Austin, 1977. Caltech, 2014-15.

Daniel I (Dan) Meiron, Ph.D., *Fletcher Jones Professor of Aeronautics and Applied and Computational Mathematics*
S.B., Massachusetts Institute of Technology, 1976; Sc.D., 1981. Research Fellow in Applied Mathematics, Caltech, 1981-83; Visiting Associate, 1984-85; Assistant Professor, 1985-89; Associate Professor, 1989-94; Professor, 1994-2000; Professor of Applied and Computational Mathematics, 2000; Professor of Applied and Computational Mathematics and Computer Science, 2001-06; Jones Professor of Applied and Computational Mathematics and Computer Science, 2006-09. Jones Professor, 2009-;Executive Officer for Applied Mathematics, 1994-98; Associate Provost for Information and Information Technology, 2000-04. Associate Director, 2009-12.

Markus Meister, Ph.D., *Anne P. and Benjamin F. Biaggini Professor of Biological Sciences*
Dipl., Technische Universitat Munchen, 1980; Ph.D., Caltech, 1987. Moore Distinguished Scholar, Caltech, 2004; Professor, 2012-13; Hanson Professor, 2013-15; Biaggini Professor, 2015-.

Michael Mello, *Lecturer in Mechanical and Civil Engineering*
B.S., Bridgewater State College, 1985; M.S., University of Rochester, 1988; Ph.D., California Institute of Technology, 2012. Caltech, 2014-17.

Jeffrey M (Jeff) Mendez, *Lecturer in Chemistry*
B.S., California Institute of Technology, 1999; Ph.D., 2008. Caltech, 2013-15.

Trevor C Merrill, *Lecturer in French*
B.A., Yale University, 2000; Ph.D., University of California, Los Angeles, 2011. Caltech, 2012-13; 2014-15.

Richard A Mewaldt, *Research Professor of Physics*
B.A., Lawrence University, 1965; M.A., Washington University (St.Louise), 1967; Ph.D., 1971. Research Fellow, Caltech, 1971-75; Senior Research Fellow, 1975-81; Lecturer, 1987; Senior Research Associate, 1981-.

Elliot Meyerowitz, Ph.D., *George W. Beadle Professor of Biology; Investigator, Howard Hughes Medical Institute*
A.B., Columbia University, 1973; M.Phil., Yale University, 1975; Ph.D., 1977. Assistant Professor, Caltech, 1980-85; Associate Professor, 1985-89; Professor, 1989-2002; Beadle Professor, 2002-. Executive Officer, 1995-2000; Chair, Division of Biology, 2000-10; Investigator, Howard Hughes Medical Institute, 2013-.

Hrushikesh Mhaskar, *Visiting Associate in Mathematics*
M.S., Indian Institute of Technology, 1976; M.S., Ohio State University, 1977; M.S., 1980; Ph.D., 1980. Caltech, 2012-16.

Thomas F (Tom) Miller, Ph.D., *Professor of Chemistry*
B.S., Texas A&M University, 2000; Ph.D., University of Oxford, 2005. Assistant Professor, Caltech, 2008-13; Professor 2013-.

Feng-Ying Ming, *Lecturer in Chinese*
B.A., Tamkang University (Taiwan), 1978; M.A., California State University, 1984; M.A., University of California (Los Angeles), 1991; Ph.D., 1999. Caltech, 2000-15.

Austin J Minnich, Ph.D., *Assistant Professor of Mechanical Engineering and Applied Physics*
B.S., University of California, Berkeley, 2006; M.S., Massachusetts Institute of Technology, 2008; Ph.D., 2011. Caltech, 2011-.

Betsy Mitchell, *Director of Athletics, Recreation and Physical Education*
M.A., University of Texas (Austin), 1991; B.S., 1998. Caltech, 2011-.

Valery P Mitrofanov, *Visiting Associate in Physics*
M.Sc., Moscow State University, 1971; Kandidat, 1975. Assistant Professor, 1981-. Caltech, 1995-2008; 2009; 2010; 2011; 2012; 2013; 2014-17.

Roger S Mong, *Visiting Associate in Theoretical Physics*
Ph.D., University of California, Berkeley, 2012. Caltech, 2015.

Hyungsik R Moon, *Visiting Associate in Economics*
B.A., Seoul National University, 1989; M.A., 1991; M.Phil., Yale University, 1996; Ph.D., 1998. Caltech, 2007; 2014.

Louis Moresi, *Visiting Associate in Geophysics*
B.A., Cambridge University, 1989; Ph.D., Oxford University, 1992. Caltech, 2013-16.

James J (Jim) Morgan, Ph.D., D.Sc.h.c., *Marvin L. Goldberger Professor of Environmental Engineering Science, Emeritus*
B.C.E., Manhattan College, 1954; M.S.E., University of Michigan, 1956; M.A., Harvard University, 1962; Ph.D., 1964; D.Sc.h.c., Manhattan College. Associate Professor of Environmental Health Engineering, Caltech, 1965-69; Professor, 1969-87; Goldberger Professor of Environmental Engineering Science, 1987-2000; Goldberger Professor Emeritus, 2000-. Academic Officer for Environmental Engineering Science, 1971-72; Dean of Students, 1972-75; Executive Officer for Environmental Engineering Science, 1974-80;1993-96; Acting Dean of Graduate Studies, 1981-84; Vice President for Student Affairs, 1980-89.

Alan M Moses, *Visiting Associate in Biology and Biological Engineering*
B.A., Columbia University School of General Studies, 2000; Ph.D., University of California, Berkeley, 2005. Caltech, 2014-15.

Michael C (Mike) Mossing, *Visiting Associate in Biology and Biological Engineering*
B.S., Michigan State University, 1980; Ph.D., University of Wisconsin, 1985. Caltech, 2015.

Olexei I Motrunich, Ph.D., *Professor of Theoretical Physics*
B.S., University of Missouri (Columbia), 1996; Ph.D., Princeton University, 2001. Assistant Professor, Caltech, 2006-12; Professor, 2012-.

Liad Mudrik-Denan, *Visiting Associate in Psychology*
M.A., Tel Aviv University, 2006; Ph.D., 2011; Ph.D., 2014. Caltech, 2015.

Duane O Muhleman, Ph.D., *Professor of Planetary Science, Emeritus*
B.S., University of Toledo, 1953; Ph.D., Harvard University, 1963. Associate Professor, Caltech, 1967-71; Professor, 1971-97; Professor Emeritus, 1997-. Staff Member, Owens Valley Radio Observatory, 1967-.

Richard M Murray, Ph.D., *Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering*
B.S., Caltech, 1985; M.S., University of California, Berkeley, 1988; Ph.D., 1990. Assistant Professor of Mechanical Engineering, Caltech, 1991-97; Associate Professor, 1997-2000; Professor, 2000-05; Professor of Control and Dynamical Systems, 2005-06; Everhart Professor of Control and Dynamical Systems; 2006-09; Everhart Professor of Control and Dynamical Systems and Bioengineering, 2009-. Chair, Engineering and Applied Science, 2000-05; Director, Information Science and Technology, 2006-2009; Interim Chair, Engineering and Applied Science, 2008-09.

Hillary Mushkin, *Research Professor of Art and Design in Mechanical and Civil Engineering*
BFA, Rhode Island School of Design, 1991; MFA, University of California, Irvine, 1994. Caltech, 2011-2017.

Jong Hyun Na, *Visiting Associate in Applied Physics and Materials Science*
B.S., Yonsei University, 2002; M.S., 2004; Ph.D., 2009. Caltech, 2015.

Jay L Nadeau, *Visiting Associate in Medical Engineering*
Ph.D., University of Minnesota, 1996. Caltech, 2002-04; 2014-15.

Stevan Nadj-Perge, *Visiting Associate in Applied Physics and Materials Science*
M.S., Belgrade University, 2006; Ph.D., Delft University of Technology, 2010. Caltech, 2015.

Yu Nakayama, *Sherman Fairchild Senior Research Assistant Professor of Theoretical Physics*
B.S., University of Tokyo, 2002, M.S., 2004, Ph.D., 2007. Caltech, 2010-13; 2014-15.

Abbas Nasiraei Moghaddam, *Visiting Associate in Bioengineering*
B.S., University of Tehran, 1995; M.S., 1998; Ph.D, Caltech, 2006. Caltech, 2010-15.

Sotirios Natsiavas, *Visiting Associate in Mechanical and Civil Engineering and Aerospace*
B.S., Aristotle University, Greece, 1982; California Institute of Technology, 1983; Ph.D., 1988. Caltech, 2015.

Thomas A Neenan, *Lecturer in Music*
B.F.A., California State University (Northridge), 1977; M.F.A., University of California (Los Angeles), 1982. Caltech, 1991-98; 1998-.

Athanasios Nenes, *Visiting Associate in Chemical Engineering*
MS, University of Miami, 97; Ph.D., Caltech, 2002. Caltech, 2015.

Dianne K Newman, Ph.D., *Professor of Biology and Geobiology; Investigator, Howard Hughes Medical Institute*
B.A., Stanford University, 1993; Ph.D., Massachusetts Institute of Technology, 1997. Clare Booth Luce Assistant Professor of Geobiology and Environmental Science and Engineering, Caltech, 2000-05; Associate Professor of Geobiology and Environmental Science and Engineering, 2005; Associate Professor of Geobiology, 2005-06; Professor of Geobiology, 2006-; Professor of Biology, 2006-. Investigator, Howard Hughes Medical Institute, 2005-07; 2010-.

Harvey B Newman, Sc.D., D.h.c., *Professor of Physics*
B.S., Massachusetts Institute of Technology, 1968; Sc.D., 1973; D.h.c., University Politehnica of Bucharest; Pavol Jozef Safarik University. Associate Professor, Caltech, 1982-90; Professor, 1990-.

William R Newman, *Eleanor Searle Visiting Professor in History*
B.A., University of North Carolina, Greensboro, 1978; M.A., Harvard University, 1980; Ph.D., 1986. Caltech, 2015.

Hien T Nguyen, *Visiting Associate in Physics; Lecturer in Physics*
Ph.D., Princeton University, 1993. Research Scientist, Jet Propulsion Laboratory, 2002-. Visiting Associate, Caltech, 2007-16; Lecturer, 2007; 2008; 2009; 2014.

Yi Ni, Ph.D., *Professor of Mathematics*
B.S., Peking University, 2001; M.S., 2003; Ph.D., Princeton University, 2007. Assistant Professor, Caltech, 2009-15; Professor, 2015-.

Marc A Nicolet, Ph.D., *Professor of Electrical Engineering and Applied Physics, Emeritus*
Ph.D., University of Basel, 1958. Assistant Professor of Electrical Engineering, Caltech, 1959-65; Associate Professor, 1965-73; Professor, 1973-88; Professor of Electrical Engineering and Applied Physics, 1988-98; Professor Emeritus, 1998-.

Shouleh Nikzad, *Visiting Associate in Astrophysics*
B.S., University of Southern California, 1982; M.S., Caltech, 1983; Ph.D., 1983. Staff, Jet Propulsion Laboratory, 1992-. Research Fellow, Caltech, 1990-91; Visiting Associate, 1992-96; 2012-15.

Ralph G Nuzzo, *Visiting Associate in Applied Physics and Materials Science*
A.B., Rutgers College, 1976; Massachusetts Institute of Technology; 1980. Caltech, 2015-18.

John P O'Doherty, Ph.D., *Professor of Psychology; Director, Caltech Brain Imaging Center*
B.A., University of Dublin (Trinity College), 1996; D.Phil., University of Oxford, 2000. Assistant Professor, Caltech, 2004-07; Associate Professor, 2007-09; Professor, 2009-; Director, Caltech Brain Imaging Center, 2013-.

Hiroshi (Hirosi Ooguri) Oguri, Ph.D., *Fred Kavli Professor of Theoretical Physics and Mathematics; Deputy Chair of Physics, Mathematics and Astronomy*
B.A., Kyoto University (Japan), 1984; M.A., 1986; Ph.D., University of Tokyo, 1989. Visiting Associate, Caltech, 1999-2000; Professor, 2000-07; Kavli Professor, 2007-; Deputy Chair, 2010-.

Yuki Oka, Ph.D., *Assistant Professor of Biology*
B.A., The University of Tokyo, 2002; Ph.D., 2007. Caltech, 2014-.

Alexandre H Okano, *Visiting Associate in Biology*
B.A., State University of Londrina, 2000; M.A., University of Campinas, 2004; Ph.D., 2008. Caltech, 2015.

Mitchio Okumura, Ph.D., *Professor of Chemical Physics*
B.S., Yale University, 1979; M.S., 1979; C.P.G.S., University of Cambridge, 1980; Ph.D., University of California, 1986. Assistant Professor, Caltech, 1988-94; Associate Professor, 1994-2003; Professor, 2003-. Executive Officer, 2006-10.

Christiane H Orcel, *Lecturer in French*
M.A., Princeton University, 1987; Ph.D., 1992. Instructor, Caltech, 1990-93; Lecturer, 1993-95; 1995-.

Peter C Ordeshook, Ph.D., *Professor of Political Science*
B.S., Massachusetts Institute of Technology, 1964; Ph.D., University of Rochester, 1969. Professor, Caltech, 1987-2009, 2013-; Harkness Professor, 2009-13. Executive Officer for the Social Sciences, 1992-95.

Christopher M Ormerod, *Taussky-Todd Instructor in Mathematics*
B.S., University of Sydney, 2004; Ph.D., 2008. Caltech, 2013-.

Victoria J Orphan, Ph.D., *Professor of Geobiology*
B.A., University of California (Santa Barbara), 1994; Ph.D., 2002. Assistant Professor,

Caltech, 2004-2010; Associate Professor, 2010; Professor, 2010-.

Michael Ortiz, Ph.D., *Frank and Ora Lee Marble Professor of Aeronautics and Mechanical Engineering*
B.S., Polytechnic University of Madrid, 1977; M.S., University of California, 1978; Ph.D., 1982. Sherman Fairchild Distinguished Scholar, Caltech, 1994-95; Professor of Aeronautics and Applied Mechanics, 1995-2000; Professor of Aeronautics and Mechanical Engineering, 2000-04; Hayman Professor, 2004-13; Marble Professor, 2013-.

Christian D Ott, Dr.rer.nat., *Professor of Theoretical Astrophysics*
Dipl., University of Heidelberg, 2003; Dr.rer. Nat., University of Potsdam, 2007. Sherman Fairchild Prize Fellow, Caltech, 2008-09; Assistant Professor, 2009-14; Professor, 2014-.

Houman Owhadi, Ph.D., *Professor of Applied and Computational Mathematics and Control and Dynamical Systems*
B.S., Ecole Polytechnique (France), 1994; M.S., Ecole Nationale des Ponts et Chaussees, 1997; Ph.D., Ecole Polytechnique Federale de Lausanne (Switzerland), 2001. Assistant Professor, Caltech, 2004-11; Professor, 2011-.

Stephen Padin, *Senior Research Associate in Astrophysics*
B.Sc, University of Manchester, 1982; Ph.D, 1985. Caltech, 2009-.

Niema M Pahlevan, *Lecturer in Medical Engineering; James Boswell Postdoctoral Scholar in Medical Engineering*
B.S., University of Tehran, 2001; M.S., California State University, Northridge, 2007; Ph.D., California Institute of Technology, 2013. Caltech, 2015.

Oskar J Painter, Ph.D., *John G Braun Professor of Applied Physics and Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute*
B.S., University of British Columbia, 1994; M.S., Caltech, 1995; Ph.D., 2001. Visiting Associate, Caltech, 2001-02; Assistant Professor, 2002-08; Associate Professor, 2008-10; Professor, 2010-13; Executive Officer, 2010-13; Co-Director, Kavli Nanoscience Institute, 2011-13, 2015-; Braun Professor, 2013-.

Thomas R Palfrey, Ph.D., *Flintridge Foundation Professor of Economics and Political Science*
B.A., University of Michigan, 1975; M.A., 1976; Ph.D., Caltech, 1981. Professor, 1986-2002; Flintridge Foundation Professor, 2003-05; 2006-. Executive Officer for the Social Sciences, 2001-02.

Iosif Papadakis, *Visiting Associate in Physics*
B.S., University of Athens, 1989; Ph.D., Queen Mary University of London, 1993. Caltech, 2014.

D A (Dimitri) Papanastassiou, *Faculty Associate in Geochemistry*
B.S. Caltech, 1965; Ph.D., 1970. Research Fellow in Physics, 1970-72; Senior Research Fellow in Planetary Science, 1972-76; Research Associate in Geochemistry, 1976-81; Senior Research Associate, 1981-99; Faculty Associate, 1999-.

Hyunwoong (HP) Park, *Visiting Associate in Environmental Science and Engineering*
Ph.D., Postech, 2004. Caltech, 2014-15.

Julie J Park, *Visiting Associate in the Humanities*
B.A., Bryn Mawr College, 1992; M.A., Princeton University, 1996; Ph.D., 2002. Caltech, 2014-15.

Carl S Parker, Ph.D., *Professor of Biochemistry*
B.A., University of Rochester, 1973; Ph.D., Washington University (St. Louis), 1977. Assistant Professor of Chemical Biology, Caltech, 1981-87; Associate Professor, 1987-92; Professor, 1992-99; Professor of Biochemistry, 1999-. Executive Officer, 2000-04.

Ryan B Patterson, Ph.D., *Assistant Professor of Physics*
B.S., Caltech, 2000; Ph.D., Princeton University, 2007. Caltech, 2010-.

Lynn K Paul, *Lecturer in Psychology*
B.A., Wheaton College, 1992; M.A., Fuller Graduate School of Psychology, 1994; M.A., Fuller Theological Seminary, 1996; Ph.D., Fuller Graduate School of Psychology, 1998. Visiting Associate, Caltech, 2004-07; Senior Research Fellow, 2006-09; Lecturer, 2008-15.

Charles W Peck, Ph.D., *Professor of Physics, Emeritus*
B.S., New Mexico College of Agricultural and Mechanical Arts, 1956; Ph.D., Caltech, 1964. Research Fellow, 1964-65; Assistant Professor, 1965-69; Associate Professor, 1969-77; Professor, 1977-2004; Professor Emeritus, 2004-. Executive Officer for Physics, 1983-86; Chair, Division of Physics, Mathematics and Astronomy, 1993-98.

Sergio Pellegrino, Ph.D., *Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering; Jet Propulsion Laboratory Senior Research Scientist Laurea,*
University of Naples, 1982; Ph.D., University of Cambridge, 1986. Professor, Caltech, 2007-2010; Kresa Professor, 2010-. Jet Propulsion Laboratory Senior Research Scientist, 2009-.

Leora Peltz, *Visiting Associate in Physics*
B.S., University of Negev, 1975; B.S., 1976; M.S., Case Western Reserve University, 1995; Ph.D., 2005. Scientist, Boeing, 2003-. Caltech, 2007-13; 2014-16.

Pietro Perona, Ph.D., *Allen E. Puckett Professor of Electrical Engineering*
D.Eng., University of Padua (Italy), 1985; Ph.D., University of California, Berkeley, 1990. Assistant Professor, Caltech, 1991-96; Professor, 1996-2008; Puckett Professor, 2008-. Director, Center for Neuromorphic Systems Engineering, 1999-2004. Executive Officer, 2006-10.

Isabelle S Peter Lashgari Faghani, *Research Assistant Professor of Biology and Biological Engineering*
Ph.D., University of Zurich, 2002. Caltech, 2011-.

Jonas C Peters, Ph.D., *Bren Professor of Chemistry; Director, Resnick Sustainability Institute*
B.S., University of Chicago, 1993; Ph.D., Massachusetts Institute of Technology; 1998. Assistant Professor, Caltech, 1999-2004; Associate Professor, 2004-06; Professor, 2006-09; Bren Professor, 2010-; Executive Officer, 2013-15; Director, 2015-.

Danny Petrasek, *Visiting Associate in Medical Engineering; Lecturer in Bioengineering.*
B.S., University of California (Los Angeles), 1980; M.D., Chicago Medical School, 1985; Ph.D., Caltech, 2002. Clinical Professor, University of California (Los Angeles) School of Medicine, 2004-. Senior Research Fellow in Applied and Computational Mathematics and Bioengineering, 2002-08; Lecturer in Bioengineering, 2005-11, 2013; 2014; Visiting Associate, Applied and Computational Mathematics and Bioengineering, 2008-13. Visiting Associate, Medical Engineering, 2013-15.

Molly Phillips, *Lecturer in Biology*
B.S., University of Oregon, 2011. Caltech, 2012; 2014; 2015.

Robert B Phillips, Ph.D., *Fred and Nancy Morris Professor of Biophysics and Biology*
B.S., University of Minnesota, 1986; Ph.D., Washington University, 1989. Clark Millikan Visiting Assistant Professor, Caltech, 1997; Professor, 2000-2011; Morris Professor, 2012-.

Thomas G Phillips, Ph.D., D.h.c., *John D. MacArthur Professor of Physics, Emeritus*
B.A., University of Oxford, 1961; M.A., 1964; Ph.D., 1964; D.h.c., l'Observatoire de Paris. Visiting Associate in Radio Astronomy, Caltech, 1978-79; Professor of Physics, 1979-2004. Altair Professor, 2004-11. MacArthur Professor, 2011-2013; MacArthur Professor, Emeritus, 2013-; Staff Member, Owens Valley Radio Observatory, 1978-85; Associate Director, Owens Valley Radio Observatory, 1981-85; Director, Caltech Submillimeter Observatory, 1986-2013.

E S (Sterl) Phinney, Ph.D., *Professor of Theoretical Astrophysics; Executive Officer for Astronomy*
B.S., Caltech, 1980; Ph.D., University of Cambridge, 1983. Assistant Professor, Caltech, 1985-91; Associate Professor, 1991-95; Professor, 1995-; Executive Officer, 2013-.

Kenneth A Pickar, *Visiting Professor of Mechanical and Civil Engineering*
B.S., City University of New York, 1961; Ph.D., University of Pennsylvania, 1966. Senior Vice President, Retired, Allied Signal Aerospace, 1993-. Visiting Professor of Engineering, Caltech, 1998; Visiting Professor of Mechanical and Civil Engineering, 1998-99; 2003-15; J. Stanley Johnson Visiting Professor of Mechanical Engineering, 1999-2003.

Niles A Pierce, Ph.D., *Professor of Applied and Computational Mathematics and Bioengineering*
B.S.E., Princeton University, 1993; D.Phil., University of Oxford, 1997. Assistant Professor of Applied Mathematics, Caltech, 2000; Assistant Professor of Applied and Computational Mathematics, 2000-04; Assistant Professor of Applied and Computational Mathematics and Bioengineering, 2004-06; Associate Professor, 2006-10; Professor, 2010-; Acting Executive Officer for Bioengineering, 2007; Executive Officer for Bioengineering, 2007-13; Executive Officer for Biological Engineering, 2013.

George Pigman, Ph.D., *Professor of English*
A.B., Harvard College, 1973; M.Phil., Yale University, 1975; Ph.D. (Comparative Literature), 1977; Ph.D., (Psychoanalysis), Southern California Psychoanalytic Institute, 1989. Assistant Professor of English, Caltech, 1977-80; Assistant Professor of Literature, 1980-83; Associate Professor, 1983-93; Professor of Literature, 1993-2004; Professor of English, 2004-. Executive Officer for the Humanities, 2003-08.

Jerome Pine, Ph.D., *Professor of Physics, Emeritus*
A.B., Princeton University, 1949; M.S., Cornell University, 1952; Ph.D., 1959. Associate Professor, Caltech, 1963-67; Professor, 1967-2014; Professor Emeritus, 2014-.

Donald H (Donnie) Pinkston, *Lecturer in Computing and Mathematical Sciences*
B.S., Caltech, 1998. Lecturer, 2005-15.

Charles R Plott, Ph.D., D.Lit.h.c., D.h.c., *William D. Hacker Professor of Economics and Political Science*
B.S., Oklahoma State University, 1961; M.S., 1964; Ph.D., University of Virginia, 1965;

D.Lit.h.c., Purdue University; D.h.c., Universite Pierre Mendes. Professor of Economics, Caltech, 1971-87; Harkness Professor, 1987-2013; Hacker Professor, 2013-.

Matthew Polisson, *Visiting Associate in Economics*
B.A., Harvard University, 2002; M.Phil., Oxford University, 2005; Ph.D., 2009. Caltech, 2015.

Hugh D (David) Politzer, Ph.D., *Richard Chace Tolman Professor of Theoretical Physics*
B.S., University of Michigan, 1969; Ph.D., Harvard University, 1974. Visiting Associate, Caltech, 1975-76; Associate Professor, 1977-79; Professor, 1979-2004; Tolman Professor, 2004-. Executive Officer for Physics, 1986-88.

James E (Jay) Polk, *Visiting Associate in Aeronautics; Lecturer in Aerospace*
B.S., Georgia Institute of Technology, 1984; M.S., Princeton University, 1986; Ph.D., 1996. Lecturer, Caltech, 1999-2002; 2005-08; 2010-14. Visiting Associate, 2007-15.

Adrian Ponce, *Visiting Associate in Chemistry*
B.S., Michigan State University, 1993; Ph.D., Caltech, 1999. Research Scientist, Jet Propulsion Laboratory, 2001-. Visiting Associate, Caltech, 2000-16.

Joyce K Poon, *Visiting Associate in Electrical Engineering*
B.A.Sc., University of Toronto, 2002; M.S., California Institute of Technology, 2003; Ph.D., 2007. Caltech, 2014.

Frank C Porter, Ph.D., *Professor of Physics*
B.S., Caltech, 1972; Ph.D., University of California, 1977. Research Fellow, Caltech, 1977-78; Weizmann Research Fellow, 1978-80; Senior Research Fellow, 1980-82; Assistant Professor, 1982-88; Associate Professor, 1988-94; Professor, 1994-.

John P Preskill, Ph.D., *Richard P. Feynman Professor of Theoretical Physics*
A.B., Princeton University, 1975; A.M., Harvard University, 1976; Ph.D., 1980. Associate Professor, Caltech, 1983-90; Professor, 1990-2002; MacArthur Professor, 2002-09; Feynman Professor, 2010-.

Thomas A (Tom) Prince, Ph.D., *Professor of Physics; Jet Propulsion Laboratory Senior Research Scientist; Director, W.M. Keck Institute for Space Studies; Deputy Executive Officer for Astronomy*
B.S., Villanova University, 1970; M.S., University of Chicago, 1972; Ph.D., 1978. Research Fellow, Caltech, 1979-80; Robert A. Millikan Research Fellow, 1980-82; Senior Research Fellow, 1982-83; Assistant Professor, 1983-86; Associate Professor, 1986-92; Professor, 1992-; Associate Director for Advanced Computer Research, 1995-2001; Director, Keck Institute, 2008-; Chief Scientist, Jet Propulsion Laboratory, 2001-06; Jet Propulsion Laboratory Senior Research Scientist, 2006-; Deputy Executive Officer, 2013-.

David Prober, Ph.D., *Assistant Professor of Biology*
B.Sc., University of Manitoba, 1995; Ph.D., University of Washington, 2002. Caltech, 2009-.

Leonid Prokhorov, *Visiting Associate in Physics*
M.S., Moscow State University, 2003; Ph.D., 2008. Caltech, 2010; 2012; 2013; 2014-17.

Leonid P Pryadko, *Visiting Associate in Theoretical Physics*
Ph.D., Stanford University, 1996. Caltech, 2013-15.

Carmie Puckett Robinson, *Visiting Associate in Biology*
B.S., Michigan State University, 1970; M.D., 1975. Professor, University of Southern California, 2000-. Senior Research Fellow, Caltech, 1986-1992; Visiting Associate, 2006-09, 2010-16.

Dale I Pullin, Ph.D., *Theodore von Karman Professor of Aeronautics*
B.Sc., University of Melbourne, 1966; B.E., University of Sydney, 1968; Ph.D., University of London (Imperial College), 1974. Visiting Associate, Caltech, 1990; Professor, 1991-2006, von Karman Professor, 2006-.

Lulu Qian, Ph.D., *Assistant Professor of Bioengineering*
B.E., Southeast University, 2002; Ph.D., Shanghai Jiao Tong University, 2007. Caltech, 2013-.

Steven R Quartz, Ph.D., *Professor of Philosophy*
B.A., University of Western Ontario (Huron College), 1986; M.A., 1988; Ph.D., University of California (San Diego), 1993. Instructor, Caltech, 1998-99; Assistant Professor, 1999-2002; Associate Professor, 2002-10; Professor, 2010-.

Matei I Radulescu, *Visiting Professor of Mechanical and Civil Engineering*
B.S., McGill University, 1997; M.S., 1999; Ph.D., 2002. Caltech, 2015.

Eric M Rains, Ph.D., *Professor of Mathematics*
B.A., Case Western Reserve University, 1991; B.S., 1991; M.S., 1991; Ph.D., Harvard University, 1995. Visiting Associate and Lecturer, Caltech, 2002; Professor, 2007-.

George A Rakuljic, *Visiting Associate in Applied Physics and Materials Science*
Ph.D., Caltech, 1987. Caltech, 2010-15.

Dinakar Ramakrishnan, Ph.D., *Taussky-Todd-Lonergan Professor of Mathematics; Executive Officer for Mathematics*
Ph.D., Columbia University, 1980. Professor, Caltech, 1988-2007; Taussky-Todd-Lonergan Professor, 2007-; Executive Officer, 2013-.

Vasumathi Raman, *Lecturer in Computing and Mathematical Sciences*
Ph.D., Cornell University, 2013. Caltech, 2015.

Christina M Ramirez, *Visiting Associate in Economics*
B.S., University of Texas, Austin, 1994; M.S., California Institute of Technology, 1997; Ph.D., 1999. Caltech, 2014-15.

Michael Ramsey-Musolf, *Visiting Associate in Physics*
Ph.D., Princeton University, 1989. Professor, University of Wisconsin (Madison), 2007-. Visiting Associate, Caltech, 2001; 2007-15; Senior Research Associate, 2001-07; Lecturer, 2005-06.

Antonio Rangel, Ph.D., *Bing Professor of Neuroscience, Behavioral Biology, and Economics*
B.Sc., Caltech, 1993; M.S., Harvard University, 1996; Ph.D., 1998. Instructor, Caltech, 1997-98; Visiting Associate, 2005-06; Associate Professor, 2006-10; Professor, 2010-13; Bing Professor, 2013-.

Evgenij A Raskatov, *Visiting Associate in Chemistry*
Diploma, Heidelberg University, 2006; Ph.D., Oxford University, 2009. Caltech, 2014-15.

Guruswami (Ravi) Ravichandran, Ph.D., D.h.c., *John E. Goode, Jr., Professor of Aerospace and Mechanical Engineering; Otis Booth Leadership Chair, Division of Engineering and Applied Science*
B.E., University of Madras (Regional Engineering College), 1981; Sc.M. (Solid Mechanics and Structures), Brown University, 1983; Sc.M. (Applied Mathematics), 1984; Ph.D., 1987; D.h.c., Paul Verlaine University. Assistant Professor, Caltech, 1990-95; Associate Professor, 1995-99; Professor, 1999-2005; Goode Professor, 2005-. Associate Director, 2008-09; Director, 2009-2015. Otis Booth Leadership Chair, 2015-.

Anthony C Readhead, Ph.D., *Robinson Professor of Astronomy, Emeritus; Director, Owens Valley Radio Observatory*
B.Sc., University of Witwatersrand (South Africa), 1968; Ph.D., University of Cambridge, 1972. Research Fellow, Caltech, 1974-75; Senior Research Fellow, 1976-79; Research Associate, 1979-81; Professor of Radio Astronomy, 1981-90; Professor of Astronomy, 1990-2000; Rawn Professor, 2000-13; Robinson Professor, 2013-15; Robinson Professor, Emeritus, 2015-; Director, Owens Valley Radio Observatory, 1981-86, 2007-; Executive Officer for Astronomy, 1990-92, 2012-13; Director, Chajnantor Observatory, 2006-2011; Jet Propulsion Laboratory Senior Research Scientist, 2006-15.

Carol W Readhead, *Lecturer in Engineering*
B.Sc., University of Witwatersrand (South Africa), 1969; Ph.D., University of Cambridge, 1976. Research Fellow in Biology, Caltech, 1977-79; Senior Research Fellow, 1980-83; Senior Research Associate, 1998-2002; Lecturer in Engineering, 2006-2014, 2015; Visiting Associate, 2011-15.

Douglas C (Doug) Rees, Ph.D., *Roscoe Gilkey Dickinson Professor of Chemistry; Investigator, Howard Hughes Medical Institute; Dean of Graduate Studies*
B.S., Yale University, 1974; Ph.D., Harvard University, 1980. Professor, Caltech, 1989-2004; Dickinson Professor, 2004-. Investigator, 1997-2002; 2005-; Full Investigator, 2002-05. Executive Officer for Chemistry, 2002-06; Executive Officer for Biochemistry and Molecular Biophysics, 2007-15; Dean of Graduate Studies, 2015-.

Gil Refael, Ph.D., *Professor of Theoretical Physics; Executive Officer for Physics*
B.S., Tel Aviv University, 1997; M.S., 1998; Ph.D., Harvard University, 2003. Assistant Professor, Caltech, 2005-2008; Associate Professor, 2008-11; Professor, 2011-; Executive Officer, 2014-.

Sarah E Reisman, Ph.D., *Professor of Chemistry; Executive Officer for Chemistry*
B.A., Connecticut College, 2001; Ph.D., Yale University, 2006. Assistant Professor, Caltech, 2008-14; Professor, 2014-. Executive Officer, 2015-.

Jean-Paul Revel, Ph.D., *Albert Billings Ruddock Professor of Biology, Emeritus*
B.Sc., University of Strasbourg, 1949; Ph.D., Harvard University, 1957. Professor of Biology, Caltech, 1971-78; Ruddock Professor, 1978-2006; Ruddock Professor Emeritus, 2006-. Dean of Students, 1996-2005.

Jason D Rhodes, *Visiting Associate in Astronomy*
B.S., Harvey Mudd College, 1994; Ph.D., Princeton University, 1999. Staff Scientist, Jet Propulsion Laboratory, 2004-. Caltech, 2004-16.

Frank R Rice, *Lecturer in Physics*
B.A., Northwestern University, 1977; M.S., Caltech, 1986; Ph.D., 1999. Lecturer, 2001-13; 2015.

Elon Rimon, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Technion-Israel Institute of Technology, 1985; M.S., Yale University, 1987; Ph.D.,

1991. Senior Lecturer, Technion - Israel Institute of Technology, 1994-. Research Fellow, Caltech, 1992-94; Visiting Associate, 1994-97; 1999-2004; 2008; 2010; 2011; 2012; 2013; 2014; 2015.

Robert C Ritchie, *Visiting Associate in History*
A.B., Occidental College, 1960; Ph.D., University of California (Los Angeles), 1970. W. M. Keck Foundation Director of Research, Huntington Library and Art Gallery, 1992-. Visiting Associate, Caltech, 1993-15; Lecturer, 1995; 1997; 1999; 2001; 2005.

Christa N Robbins, *Mellon Caltech-Huntington Postdoctoral Instructor in Art History*
B.F.A., Colorado State University, 1997; M.A., The University of Chicago, 2002; Ph.D., 2010. Caltech, 2013-15.

John D Roberts, Ph.D., Dr.rer.nat.h.c., Sc.D.h.c., D.Sc.h.c., *Institute Professor of Chemistry, Emeritus*
B.A., University of California (Los Angeles), 1941; Ph.D., 1944; Dr.rer.nat.h.c., University of Munich; Sc.D.h.c., Temple University; D.Sc.h.c., University of Wales; University of Notre Dame; Scripps Research Institute. Research Associate, Caltech, 1952-53; Professor, 1953-72; Institute Professor, 1972-88; Institute Professor Emeritus, 1988-; Lecturer 1988-92. Chairman, Division of Chemistry and Chemical Engineering, 1963-68; Acting Chairman, 1972-73; Provost and Vice President, Dean of the Faculty, 1980-83.

Richard W Roll, Ph.D., *Linde Institute Professor of Finance*
B.A.E., Auburn University, 1961; M.B.A., University of Washington, 1963; Ph.D., University of Chicago, 1968. Caltech, Linde Institute Professor, 2013-.

Alton D Romig, *Visiting Associate in Physics*
Ph.D., Lehigh University, 1979. Caltech, 2013-15.

Sylvie Ronel, *Visiting Associate in Aerospace*
B.S., Institut National des Sciences Appliquées de Lyon, 1986; Ph.D., 1994. Caltech, 2015-16.

Ares J Rosakis, Ph.D., *Theodore von Karman Professor of Aeronautics and Mechanical Engineering*
B.Sc., University of Oxford, 1978; Sc.M., Brown University, 1980; Ph.D., 1982. Assistant Professor of Aeronautics and Applied Mechanics, Caltech, 1982-88; Associate Professor, 1988-93; Professor, 1993-2000; Professor of Aeronautics and Mechanical Engineering, 2000-04; von Karman Professor, 2004-; Director, Graduate Aerospace Laboratories, 2004-09; Chair, 2009-13; Otis Booth Leadership Chair, 2013-15.

Phoebus Rosakis, *Visiting Associate in Aerospace*
B.S., Brown University, 1983; M.S., Caltech, 1984; Ph.D., 1989. Caltech, 2011-16.

Paul A Rosen, *Visiting Associate in Geophysics*
B.S., University of Pennsylvania, 1981; M.S., 1982; Ph.D., Stanford University, 1989. Technical Group Supervisor, Jet Propulsion Laboratory, 1992-. Visiting Associate, Caltech, 1998-2015; Lecturer, 2000-03; 2005.

Robert A Rosenstone, Ph.D., *Professor of History, Emeritus*
B.A., University of California (Los Angeles), 1957; Ph.D., 1965. Visiting Assistant Professor, Caltech, 1966-68; Assistant Professor, 1968-69; Associate Professor, 1969-75; Professor, 1975-2012; Professor Emeritus, 2012-. Executive Officer for the Humanities, 1983-86.

Jean-Laurent Rosenthal, Ph.D., *Rea A. and Lela G. Axline Professor of Business Economics; Chair, Division of the Humanities and Social Sciences*
B.A., Reed College, 1984; Ph.D., Caltech, 1988. Professor of Economics, 2006-2008; Axline Professor of Business Economics, 2008-. Executive Officer, 2007-13; Division Chair, 2014-.

Anatol Roshko, Ph.D., *Theodore von Kármán Professor of Aeronautics, Emeritus*
B.Sc., University of Alberta, 1945; M.S., Caltech, 1947; Ph.D., 1952. Research Fellow, 1952-54; Senior Research Fellow, 1954-55; Assistant Professor, 1955-58; Associate Professor, 1958-62; Professor, 1962-85; von Kármán Professor, 1985-94; von Kármán Professor Emeritus, 1994-. Acting Director, Graduate Aeronautical Laboratories, 1985-87.

Brian D Ross, *Visiting Associate in Medical Engineering*
B.Sc., University College London, 1958; M.B.B.S., 1961; D.Phil., University of Oxford (Trinity College), 1966. Director, Clinical Spectroscopy Laboratory, Huntington Medical Research Institutes, 1986-. Caltech, 1988-2008; 2014; 2015.

Ian Ross, *Visiting Associate in Biology and Biological Engineering*
B.Sc., McGill University, 1981; M.D., Queens University, 1985; M.Sc., University of Toronto, 1992. Provisional Staff, Huntington Memorial Hospital, 2005-. Caltech, 2008-16.

George R Rossman, Ph.D., *Professor of Mineralogy*
B.S., Wisconsin State University, 1966; Ph.D., Caltech, 1971. Instructor, 1971; Assistant Professor, 1971-77; Associate Professor, 1977-83; Professor, 1983-2008; 2015-. McMillan Professor, 2008-15. Divisional Academic Officer for Geological and Planetary Sciences, 1999-2008.

Paul W Rothemund, *Research Professor of Bioengineering, Computing and Mathematical Sciences, and Computation and Neural Systems*
B.S., Caltech, 1994; Ph.D., University of Southern California, 2001. Visiting Associate, Caltech, 2001; Beckman Senior Research Fellow, 2001-04; Senior Research Fellow, Computation and Neural Systems and Computer Science, 2004-08; Senior Research Associate, 2008-2015; Research Professor, 2015-.

Ellen Rothenberg, Ph.D., *Albert Billings Ruddock Professor of Biology*
A.B., Harvard University, 1972; Ph.D., Massachusetts Institute of Technology, 1977. Assistant Professor, Caltech, 1982-88; Associate Professor, 1988-94; Professor, 1994-2007; Ruddock Professor, 2007-.

Brandon Rothrock, *Lecturer in Mechanical and Civil Engineering*
B.S., University of Washington, 2000; M.S., University of California, Los Angeles, 2011; Ph.D., 2013. Lecturer, 2015.

Michael L Roukes, Ph.D., *Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering*
B.A., University of California (Santa Cruz), 1978; Ph.D., Cornell University, 1985. Associate Professor, Caltech, 1992-96; Professor of Physics, 1996-2002; Professor of Physics, Applied Physics, and Bioengineering, 2002-11; Abbey Professor, 2011-; Director, Kavli Nanoscience Institute, 2004-06; Co-Director, 2008-2013.

Ueli Rutishauser, *Visiting Associate in Biology and Bioengineering*
B.S., University of Applied Sciences, Rapperwil, 2003; Ph.D., California Institute of Technology, 2008. Caltech, 2013-15.

David B Rutledge, Ph.D., *Kiyo and Eiko Tomiyasu Professor of Engineering*
B.A., Williams College, 1973; M.A., University of Cambridge, 1975; Ph.D., University of California, 1980. Assistant Professor, Caltech, 1980-84; Associate Professor, 1984-89; Professor, 1989-2001; Tomiyasu Professor, 2001-. Executive Officer for Electrical Engineering, 1999-2002; Chair, Division of Engineering and Applied Science, 2005-08.

Michael S Ryoo, *Lecturer in Mechanical and Civil Engineering*
B.S., Korea Advanced Institute of Science & Technology, 2004; M.S., University of Texas, 2008; Ph.D., 2008. Caltech, 2015.

Rolf Sabersky, Ph.D., *Professor of Mechanical Engineering, Emeritus*
B.S., Caltech, 1942; M.S., 1943; Ph.D., 1949. Assistant Professor, 1949-55; Associate Professor, 1955-61; Professor, 1961-88; Professor Emeritus, 1988-.

John E Sader, *Visiting Associate in Physics*
B.S., University of New South Wales, 1989; Ph.D., 1993. Professor, University of Melbourne, 2008-. Caltech, 2009; 2010; 2012-15.

Kota Saito, Ph.D., *Assistant Professor of Economics*
M.A., University of Tokyo, 2007; Ph.D., Northwestern University, 2011. Caltech, 2011-.

Jason B Saleeby, Ph.D., *Professor of Geology, Emeritus*
B.S., California State University (Northridge), 1972; Ph.D., University of California (Santa Barbara), 1975. Associate Professor, Caltech, 1978-88; Professor, 1988-2015; Professor Emeritus, 2015-.

Benjamin A Saltzman, *Weisman Postdoctoral Instructor in Medieval British Literature*
B.A., Pace University, 2007; Ph.D., University of California (Berkeley), 2014. Caltech, 2014-16.

Charles Sammis, *Visiting Associate in Aerospace*
B.S., Brown University, 1965; M.S., California Institute of Technology, 1968; Ph.D., 1971. Caltech, 2014-15.

Konrad H Samwer, *Visiting Associate in Applied Physics and Materials Science*
Ph.D., University of Goettingen (Germany), 1981. Professor, 1990-. Research Fellow, Caltech, 1981-82; Visiting Associate, 1987; 1994; 1998-2000; 2004-05; 2007; 2009-17.

Stanley P (Stan) Sander, *Visiting Associate in Planetary Science*
B.A., Pomona College, 1974; M.S., Caltech, 1975; Ph.D.,1980. Senior Research Scientist, Jet Propulsion Laboratory, 1996-. Visiting Associate in Planetary Science and Environmental Engineering Science, Caltech, 1998-2005; Lecturer in Geology and Planetary Sciences and Environmental Engineering Science, 1998-2004; Visiting Associate in Planetary Science and Environmental Engineering and Science, 2005; Visiting Associate in Planetary Science, 2006-15.

Anneila I Sargent, Ph.D., D.Sc.h.c., *Ira S. Bowen Professor of Astronomy*
B.Sc., University of Edinburgh, 1963; M.S., Caltech, 1967; Ph.D., 1977; D.Sc.h.c., University of Edinburgh. Research Fellow, 1977-79; Member of the Professional Staff, 1979-88; Senior Research Fellow, 1988-90; Senior Research Associate, 1990-98; Professor, 1998-2004; Rosen Professor, 2004-13; Bowen Professor, 2013-; Associate Director, Owens Valley Radio Observatory, 1992-96; Executive Director, 1996-98; Director, 1998-2007; Director, Interferometry Science Center, 2000-03; Director, Michelson Science Center, 2003; Vice President, 2007-15.

Re'em Sari, *Visiting Associate in Astrophysics*
B.Sc. (Physics), Ben-Gurion University of the Negev, 1991; B.Sc. (Mathematics), 1992; M.Sc., Hebrew University, 1994; Ph.D., 1998. Fairchild Senior Research Fellow in Astrophysics, Caltech, 1998-2003; Lecturer in Physics, 2001; Lecturer in Planetary Science, 2001. Associate Professor, 2003-2009; Visiting Associate, 2010-16.

Bangalore S Sathyaprakash, *Visiting Associate in Physics*
B.Sc., Bangalore University (India), 1979; M.S., Indian Institute of Technology, 1981; Ph.D., 1987. Scientist, Inter University Center for Astronomy and Astrophysics, 1993-. Senior Lecturer, Cardiff University, 1999-. Caltech, 1996; 2000; 2014-15.

Tilman Sauer, *Visiting Associate in History*
Dipl., Free University (Berlin), 1990; Ph.D., 1994. Visiting Associate, Caltech, 2001-03; Senior Research Fellow, 2003-05; Senior Research Associate, 2005-; Lecturer, 2006; 2008; 2009.

Ankur Saxena, *Research Assistant Professor of Biology and Biological Engineering*
B.S., University of Texas (Austin), 1999; Ph.D., University of Texas (Southwestern Medical Center), 2005. Caltech, 2014-.

William P Schaefer, *Senior Research Associate in Chemistry, Emeritus*
B.S., Stanford University, 1952; M.S., University of California (Los Angeles), 1954; Ph.D., 1960. Instructor, Caltech, 1960-62; Assistant Professor, 1962-66; Senior Research Fellow, 1968-77; Research Associate, 1977-81; Senior Research Associate, 1981-94; Senior Research Associate Emeritus, 1994-. Assistant Director of Admissions, 1968-73; Regristrar, 1971-77; Director of Financial Aid, 1973-77.

Hayden Schaeffer, *von Karman Instructor in Computing and Mathematical Sciences*
University of California, Los Angeles, Ph.D., 2013. Caltech, 2014-16.

Daniel Scharf, *Lecturer in Aerospace*
B.S., University of Minnesota, 1995; M.S., University of Michigan, Ann Arbor, 1997; Ph.D, 2001. Caltech, 2013; 2014; 2015.

Mark Scheel, *Senior Research Associate in Physics*
Ph.D., Cornell University, 1996. Senior Research Fellow, Caltech, 2005-; Lecturer, 2005-06; 2014-15; Research Professor, 2015-.
Axel Scherer, Ph.D., Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics B.S., New Mexico Institute of Mining and Technology, 1981; M.S., 1982; Ph.D., 1985. Associate Professor of Electrical Engineering, Caltech, 1993-95; Professor, 1995; Professor of Electrical Engineering and Applied Physics, 1995-96; Professor of Electrical Engineering, Applied Physics, and Physics, 1996-2000; Neches Professor, 2000-. Director, Kavli Nanoscience Institute, 2006-08; Co-Director, 2008-11.

Maarten Schmidt, Ph.D., *Francis L. Moseley Professor of Astronomy, Emeritus*
Ph.D., University of Leiden, 1956; Sc.D., Yale University, 1966. Associate Professor, Caltech, 1959-64; Professor, 1964-81; Institute Professor, 1981-87; Moseley Professor, 1987-96; Moseley Professor Emeritus, 1996-. Executive Officer for Astronomy, 1972-75; Chairman, Division of Physics, Mathematics and Astronomy, 1976-78; Director, Hale Observatories, 1978-80.

Tapio Schneider, Ph.D., *Frank J. Gilloon Professor of Environmental Science and Engineering*
Vordipl., Albert-Ludwigs-Universitat Freiburg, 1993; Ph.D., Princeton University, 2001. Assistant Professor, Caltech, 2002-08; Associate Professor, 2008-09; Professor, 2009-10; Gilloon Professor, 2010-; Director, Linde Center, 2011-12; Executive Officer, 2011-12.

Peter Schroeder, Ph.D., *Shaler Arthur Hanisch Professor of Computer Science and Applied and Computational Mathematics; EAS Division Deputy Chair*
B.S., Technical University of Berlin, 1987; M.S., Massachusetts Institute of Technology, 1990; M.A., Princeton University, 1992; Ph.D., 1994. Assistant Professor of Computer Science, Caltech, 1995-98; Associate Professor, 1998-2000; Associate Professor of Computer Science and Applied and Computational Mathematics, 2000-01; Professor, 2001-13; Hanisch Professor, 2013-; Division Deputy Chair, 2012-; Acting Director, 2013-14.

Leonard J Schulman, Ph.D., *Professor of Computer Science*
B.S., Massachusetts Institute of Technology, 1988; Ph.D., 1992. Associate Professor, Caltech, 2000-05; Professor, 2005-.

Wolfram Schultz, *Visiting Associate in Neuroscience*
B.A., Universities of Hamburg and Heidelberg, 1971; M.D., University of Heidelberg, 1972; Ph.D., University of Fribourg, 1981. Professor, University of Cambridge, 2001-. Visiting Associate, Caltech, 2004-05; 2007; 2008; 2009; 2010-12; 2013-15. Moore Distinguished Scholar, 2005-06.

Keith C Schwab, Ph.D., *Professor of Applied Physics*
B.A., University of Chicago, 1990; Ph.D., University of California, 1996. Associate Professor, Caltech, 2009-10; Professor, 2010-; Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute, 2013-15.

John H Schwarz, Ph.D., *Harold Brown Professor of Theoretical Physics, Emeritus*
A.B., Harvard College, 1962; Ph.D., University of California, 1966. Research Associate, Caltech, 1972-81; Senior Research Associate, 1981-85; Professor of Theoretical Physics, 1985-89; Brown Professor, 1989-2014; Brown Professor Emeritus, 2015-.

Nicholas Z (Nick) Scoville, Ph.D., *Francis L. Moseley Professor of Astronomy*
B.A., Columbia University, 1967; Ph.D., 1972. Professor, Caltech, 1984-96; Moseley Professor, 1996-. Director, Owens Valley Radio Observatory, 1986-96. Executive Officer for Astronomy, 2000-04.

Thayer Scudder, Ph.D., *Professor of Anthropology, Emeritus*
A.B., Harvard College, 1952; Ph.D., Harvard University, 1960. Assistant Professor, Caltech, 1964-66; Associate Professor, 1966-69; Professor, 1969-2000; Professor Emeritus, 2000-.

John H Seinfeld, Ph.D., D.Sc.h.c., *Louis E. Nohl Professor and Professor of Chemica*l *Engineering*
B.S., University of Rochester, 1964; Ph.D., Princeton University, 1967; D.Sc.h.c., University of Patras; Carnegie Mellon University; Clarkson University. Assistant Professor, Caltech, 1967-70; Associate Professor, 1970-74; Professor, 1974-; Nohl Professor, 1979-. Executive Officer for Chemical Engineering, 1974-90; Chair, Division of Engineering and Applied Science, 1990-2000.

Shaunak Sen, *Visiting Associate in Computing and Mathematical Sciences*
B.S., Indian Institute of Technology, Kanpur, 2003; Ph.D., California Institute of Technology, 2011Caltech, 2012-15.

Alex L Sessions, Ph.D., *Professor of Geobiology*
B.A., Williams College, 1991; M.Sc., Dartmouth College, 1996; Ph.D., Indiana University (Bloomington), 2001. Assistant Professor, Caltech, 2003-10; Associate Professor, 2010; Professor, 2010-.

Mona Shahgholi, *Lecturer in Chemistry*
B.S., Oklahoma State University, 1979; M.S., University of Colorado, 1989; Ph,D., University of Tennessee, 1993. Caltech, 2008; 2009; 2010; 2011; 2013; 2014; 2015.

Shu-ou Shan, Ph.D., *Professor of Chemistry; Executive Officer for Biochemistry and Molecular Biophysics*
B.S., University of Maryland, 1994; Ph.D., Stanford University, 2000. Assistant Professor, Caltech, 2005-11; Professor, 2011-. Executive Officer, 2015-.

Mikhail Shapiro, Ph.D., *Assistant Professor of Chemical Engineering*
B.S., Brown University, 2004; Ph.D., Massachusetts Institute of Technology, 2008. Visiting Associate, Caltech, 2013; Assistant Professor, 2014-.

Andrew A Shapiro-Scharlotta, *Visiting Associate in Aerospace; Lecturer in Applied Physics and Materials Science*
B.S., University of California, 1981; M.S., University of California (Los Angeles), 1989; Ph.D., University of California (Irvine), 1998. Principal Engineer, Jet Propulsion Laboratory, 2002-. Caltech, 2008-16.

Adam Sheffer, *Harry Bateman Instructor in Mathematics*
B.S., Tel-Aviv University, 2004; M.S., 2009; Ph.D., 2014. Caltech, 2014-17.

Joseph E Shepherd, Ph.D., *C. L. Kelly Johnson Professor of Aeronautics and Mechanical Engineering; Vice President for Student Affairs*
B.S., University of South Florida, 1976; Ph.D., Caltech, 1981. Associate Professor, 1993-99; Professor of Aeronautics, 1999-2005; Professor of Aeronautics and Mechanical Engineering, 2006-08; Johnson Professor, 2008-; Dean of Graduate Studies, 2009-15. Vice President, 2015-.

Robert P (Bob) Sherman, Ph.D., *Professor of Economics and Statistics*
B.A., Marquette University, 1978; M.A., University of Louisville, 1985; M.Phil., Yale University, 1987; Ph.D., 1991. Assistant Professor, Caltech, 1996-99; Associate Professor, 1999-2005; Professor, 2005-.

Drora Shevy, *Visiting Associate in Chemical Engineering*
M.D., Sackler School of Graduate Biomedical Sciences, 1985; Ph.D., 1985. Director, Orbits Lightwave, Inc., 2001-. Caltech, 2007-09; 2010-12; 2014-15.

Shinsuke (Shin) Shimojo, Ph.D., *Gertrude Baltimore Professor of Experimental Psychology*
B.A., University of Tokyo, 1978; M.A., 1980; Ph.D., Massachusetts Institute of Technology, 1985. Associate Professor, Caltech, 1997-98; Professor, 1999-2010; Baltimore Professor, 2010-.

Matthew S (Matt) Shum, Ph.D., *Professor of Economics*
B.A., Columbia University, 1992; Ph.D., Stanford University, 1998. Caltech, 2008-.

Athanassios G (Thanos) Siapas, Ph.D., *Professor of Computation and Neural Systems*
B.S., Massachusetts Institute of Technology, 1990; M.S., 1992; Ph.D., 1996. Assistant Professor, Caltech, 2002-08; Bren Scholar 2003-08; Associate Professor, 2008-10; Professor, 2010-.

Peter Siegel, *Visiting Associate in Electrical Engineering*
B.A., Colgate University, 1975; M.S., Columbia University, 1983; M.Ph., 1983; Ph.D., 1983. Caltech, 2002; 2007-10; 2014-16.

Elwadura Prabath S (Prabath) Silva, *Harry Bateman Instructor in Mathematics*
B.Sc., University of Colombo, 2007; Ph.D., Indiana University, 2014. Caltech, 2014-17.

Leon T Silver, Ph.D., *W. M. Keck Foundation Professor for Resource Geology, Emeritus*
B.S., University of Colorado, 1945; M.S., University of New Mexico, 1948; Ph.D., Caltech, 1955. Assistant Professor of Geology, 1955-62; Associate Professor, 1962-65; Professor, 1965-83; Keck Professor, 1983-96; Keck Professor Emeritus, 1996-.

Barry M Simon, Ph.D., D.Sc.h.c., *International Business Machines Professor of Mathematics and Theoretical Physics*
A.B., Harvard College, 1966; Ph.D., Princeton University, 1970; D.Sc.h.c., Technion-Israel Institute of Technology; University of Wales Swansea; Ludwig-Maximilians-Universitat Munchen. Sherman Fairchild Distinguished Scholar, Caltech, 1980-81; Professor, 1981-84; International Business Machines Professor, 1984-. Executive Officer for Mathematics, 1997-2003; 2009-13.

Melvin I (Mel) Simon, Ph.D., *Anne P. and Benjamin F. Biaggini Professor of Biological Sciences, Emeritus*
B.S., City College of New York, 1959; Ph.D., Brandeis University, 1963. Professor, Caltech, 1982-86; Biaggini Professor, 1986-2005; Biaggini Professor Emeritus, 2005-; Chair, Division of Biology, 1995-2000.

Mark Simons, Ph.D., *Professor of Geophysics*
B.S., University of California (Los Angeles), 1989; Ph.D., Massachusetts Institute of Technology, 1995. Assistant Professor, Caltech, 1997-2003; Associate Professor, 2003-2007; Professor, 2007-.

Annette J Smith, Ph.D., *Professor of Literature, Emeritus*
B.A., University of Paris (Sorbonne), 1947; M.A., 1950; Ph.D., 1970. Visiting Assistant Professor of French, Caltech, 1970-71; Lecturer, 1971-81; Associate Professor, 1982-85; Professor, 1985-92; Professor of Literature Emeritus, 1993-.

Douglas L Smith, *Lecturer in Engineering*
B.S., Waynesburg College, 1980; Graduate Certificate, University of California, Santa Cruz, 1982. Caltech, 2014; 2015.

Erik Snowberg, Ph.D., *Professor of Economics and Political Science; Master of Student Houses*
S.B., Massachusetts Institute of Technology, 1999; Ph.D., Stanford University, 2008. Assistant Professor, Caltech, 2008-11; Associate Professor, 2011-12; Professor, 2012-; Master of Student Houses, 2014-.

G J (Jeff) Snyder, *Faculty Associate in Applied Physics and Materials Science*
B.A., Cornell University, 1991; Ph.D., Stanford University, 1997. Visiting Associate, Caltech, 2000-06; Lecturer, 2003; 2007-08. Faculty Associate, 2006-16.

B T Soifer, Ph.D., *Harold Brown Professor of Physics; Director, Spitzer Science Center*
B.S., Caltech, 1968; Ph.D., Cornell University, 1972. Senior Research Fellow, Caltech, 1978-81; Senior Research Associate, 1981-89; Professor, 1989-2015; Brown Professor, 2015-; Director, Space Infrared Telescope Facility (SIRTF) Science Center, 1997-2004. Director, Spitzer Science Center, 2004-; Deputy Chair, 2008-10; Acting Chair, 2010; Division Chair, 2010-14; Kresa Leadership Chair, 2014-15.

Pablo R Solis, *Olga Taussky and John Todd Instructor in Mathematics*
B.S., Massachusetts Institute of Technology, 2008; Ph.D., University of California, Berkeley, 2014. Caltech, 2014-17.

Hyun-Kon Song, *Visiting Associate in Applied Physics and Materials Science*
B.S., Pohang University of Science and Technology, 1994; M.S., 1996; Ph.D., 2000. Caltech, 2015-16.

Manuel Soriaga, *Visiting Associate in Chemistry*
B.S., University of San Carlos, 1970; Ph.D., University of Hawaii, 1978. Caltech, 2012-15.

Michael L Spezio, *Visiting Associate in Psychology*
B.S., Case Western Reserve University, 1988; Ph.D., Cornell University, 1994; M.Div., Pittsburgh Theological Seminary, 1996; Ph.D., University of Oregon, 2002. Assistant Professor, Scripps College, 2007-. Lecturer, Caltech, 2006-07; Visiting Associate, 2007-15.

Maria Spiropulu, Ph.D., *Professor of Physics*
B.Sc., Aristotle University of Thessaloniki, 1993; M.A., Harvard University, 1995; Ph.D., 2000. Associate Professor, Caltech, 2008-11; Professor, 2011-.

Mark Stalzer, *Visiting Associate in Computational Science*
B.S., California State University, Northridge, 1984; M.S., University of Southern California, 1989; Ph.D., 1993. Caltech 2010-15.

Angelike Stathopoulos, Ph.D., *Professor of Biology*
B.A., University of California, 1992; Ph.D., Stanford University, 1998. Assistant Professor, Caltech, 2005-11; Professor, 2011-.

Andrew Steele, *Broad Senior Research Fellow in Brain Circuitry, Lecturer in Biology*
A.B., University of Chicago, 2001; Caltech, 2008-2013, 2015.

Charles (Chuck) Steidel, Ph.D., *Lee A. DuBridge Professor of Astronomy*
A.B., Princeton University, 1984; Ph.D., Caltech, 1990. Assistant Professor, 1995-97; Associate Professor, 1997-98; Professor 1998-2004; DuBridge Professor, 2004-. Executive Officer for Astronomy, 2004-2007.

Eric D Stemp, *Visiting Associate in Chemistry*
B.S., University of Denver, 1987; M.S., Northwestern University, 1988; Ph.D., 1993. Assistant Professor, Mount St. Mary's College, 1996-. Research Fellow, Caltech, 1993-96; Visiting Associate, 1996-2015.

Paul W Sternberg, Ph.D., *Thomas Hunt Morgan Professor of Biology; Investigator, Howard Hughes Medical Institute*
B.A., Hampshire College, 1978; Ph.D., Massachusetts Institute of Technology, 1984. Assistant Professor, Caltech, 1987-92; Associate Professor, 1992-96; Professor, 1996-2004; Morgan Professor, 2004-. Associate Investigator, 1992-97; Investigator, 1997-.

David J (Dave) Stevenson, Ph.D., D.S.c., *Marvin L. Goldberger Professor of Planetary Science*
B.S., Victoria University (New Zealand), 1971; M.S., 1972; Ph.D., Cornell University, 1976; D.S.c., Victoria University. Associate Professor, Caltech, 1980-84; Professor, 1984-95; Van Osdol Professor, 1995-2011; Goldberger Professor, 2011-. Chair, Division of Geological and Planetary Sciences, 1989-94.

Joann M Stock, Ph.D., *Professor of Geology and Geophysics*
B.S., Massachusetts Institute of Technology, 1981; M.S., 1981; Ph.D., 1988. Visiting Assistant Professor, Caltech, 1990; Associate Professor, 1992-98; Professor, 1998-.

Edward M Stolper, Ph.D., D.Sc.h.c., *Provost; William E. Leonhard Professor of Geology; Carl and Shirley Larson Provostial Chair*
A.B., Harvard College, 1974; M.Phil., University of Edinburgh, 1976; Ph.D., Harvard University, 1979; D.Sc.h.c., University of Edinburgh; D.Phil.h.c., Hebrew University. Assistant Professor, Caltech, 1979-82; Associate Professor, 1982-83; Professor, 1983-90; Leonhard Professor, 1990-. Acting Executive Officer for Geochemistry, 1989; Executive Officer, 1989-94; Chair, Division of Geological and Planetary Sciences, 1994-2004; Acting Provost, 2004; Provost, 2007-13; Larson Provostial Chair, 2013-; Interim President, 2013-2014.

Brian M Stoltz, Ph.D., *Professor of Chemistry*
B.A., B.S., Indiana University of Pennsylvania, 1993; M.A., Yale University, 1996; Ph.D., 1997. Assistant Professor, Caltech, 2000-06; Associate Professor, 2006-07; Professor, 2007-; Bowles Professor, 2007-12. Executive Officer, 2010-12.

Edward C Stone, Ph.D., D.Sc.h.c., *David Morrisroe Professor of Physics; Vice Provost for Special Projects*
S.M., University of Chicago, 1959; Ph.D., 1964; D.Sc.h.c., Harvard University; Washington University; University of Chicago; University of Southern California. Research Fellow, Caltech, 1964-66; Senior Research Fellow, 1967; Assistant Professor, 1967-71; Associate Professor, 1971-76; Professor, 1976-94; Morrisroe Professor, 1994-. Chairman, Division of Physics, Mathematics and Astronomy, 1983-88; Vice President for Astronomical Facilities, 1988-90; Vice President and Director of the Jet Propulsion Laboratory, 1991-2001; Vice Provost, 2004-.

Ellen G Strauss, *Senior Research Associate in Biology, Emeritus*
B.A., Swarthmore College, 1960; Ph.D., Caltech, 1966. Research Fellow, 1969-73; Senior Research Fellow, 1973-84; Senior Research Associate, 1984-2007; Senior Research Associate Emeritus, 2007-.

James H Strauss, Ph.D., *Ethel Wilson Bowles and Robert Bowles Professor of Biology, Emeritus*
B.S., Saint Mary's University, 1960; Ph.D., Caltech, 1967. Assistant Professor, 1969-75; Associate Professor, 1975-83; Professor, 1983-93; Bowles Professor, 1993-2007; Bowles Professor Emeritus, 2007-. Executive Officer for Molecular and Cellular Biology, 1980-89.

Piotr Sulkowski, *Visiting Associate in Physics*
M.Sc., Warsaw University, 2002; Ph.D., 2007. Caltech, 2012-15.

Xiaodan Sun, *Visiting Associate in Mechanical and Civil Engineering*
B.S., Harbin Institute of Technology, 2003; M.S., 2004; Ph.D., 2010. Caltech, 2014-15.

Raman Sundrum, Ph.D., *Moore Distinguished Scholar*
B.Sc., University of Sidney, 1984; Ph.D., Yale University, 1990. Caltech, 2015.

Rajasekaran Swaminathan, *Visiting Associate in Applied Physics and Materials Science*
Btech, Indian Institute of Technology, 2000; Ph.D., Carnegie Mellon University, 2005. Caltech, 2014-15.

Tabitha L Swan-Wood, *Visiting Associate in Applied Physics & Materials Science*
B.S., University of California (Riverside), 2000; M.S., Caltech, 2002; Ph.D., 2005. Part-time Faculty, California State University (Channel Islands), 2005-. Caltech, 2005-07; 2014-15.

Luke A Sweatlock, *Visiting Associate in Applied Physics and Materials Science*
B.S., Cornell University, 2001; M.S., California Institute of Technology, 2003; Ph.D., 2008. Caltech, 2012-16.

Noel M Swerdlow, *Visiting Associate in History*
B.A., University of California (Los Angeles), 1964; M.A., Yale University, 1967; Ph.D., 1968. Professor, University of Chicago, 1982-. Visiting Associate in History, Caltech, 2008, 2010-18; Visiting Professor, 2008-09.

Bela Szilagyi, *Senior Research Fellow in Physics*
Ph.D., University of Pittsburg, 2000. Caltech, 2010-16.

Yu-Chong Tai, Ph.D., *Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering; Executive Officer for Medical Engineering*
B.S., National Taiwan University, 1981; M.S., University of California, 1986; Ph.D., 1989. Assistant Professor of Electrical Engineering, Caltech, 1989-95; Associate Professor, 1995-2000; Professor, 2000-05; Professor of Electrical Engineering and Mechanical Engineering, 2005-13; Rosen Professor, 2013-; Executive Officer for Electrical Engineering, 2005-2008; Executive Officer, 2013-.

Omer Tamuz, Ph.D., *Assistant Professor of Economics*
B.Sc., Tel Aviv University, 2006; M.Sc., Weizman Institute of Science, 2010; Ph.D., 2013. Caltech, 2015-.

Ao (Kevin) Tang, *Visiting Associate in Electrical Engineering*
B.S., Tsonghua University, 1999; Ph.D., California Institute of Technology, 2006. Caltech, 2014-15.

Robert D Tanner, *Visiting Associate in Chemical Engineering*
B.S., University of Michigan, 1962; M.S., 1963; Ph.D, Case Western Reserve, 1967. Caltech, 2010-16.

Hugh P Taylor, Ph.D., *Robert P. Sharp Professor of Geology, Emeritus*
B.S., Caltech, 1954; A.M., Harvard University, 1955; Ph.D., Caltech, 1959. Assistant Professor, 1959-61; Research Fellow, 1961; Assistant Professor, 1962-64; Associate Professor, 1964-69; Professor, 1969-81; Sharp Professor, 1981-2002; Sharp Professor Emeritus, 2002-. Executive Officer for Geology, 1987-94.

Joao Teixeira, *Visiting Associate in Enviornmental Science and Engineering*
Ph.D., University of Lisbon, 2000. Caltech, 2010-16.

Saul A Teukolsky, *Visiting Associate in Theoretical Astrophysics*
Ph.D., Caltech, 1973. Caltech, 2015-16.

Andrew F Thompson, Ph.D., *Assistant Professor of Environmental Science and Engineering*
B.S., Dartmouth College, 2000; C.A.S., University of Cambridge, 2001, M.Phil., 2002; Ph.D., Scripps Institute of Oceanography, 2006. Caltech, 2011-.

Kip S Thorne, Ph.D, D.Sc.h.c., D.h.c., L.H.D.h.c., *Richard P. Feynman Professor of Theoretical Physics, Emeritus*
B.S., Caltech, 1962; Ph.D., Princeton University, 1965; D.Sc.h.c., Illinois College; Utah State University; University of Chicago; D.h.c., Moscow University; University of Glasgow; L.H.D.h.c., The Claremont Graduate University. Research Fellow in Physics, Caltech, 1966-67; Associate Professor of Theoretical Physics, 1967-70; Professor, 1970-91; William R. Kenan Professor, 1981-91; Feynman Professor, 1991-2009; Feynman Professor Emeritus, 2009-.

David A Tirrell, Ph.D., D.h.c., *Ross McCollum-William H. Corcoran Professor and Professor of Chemistry and Chemical Engineering; Director, Beckman Institute*
B.S., Massachusetts Institute of Technology, 1974; M.S., University of Massachusetts, 1976; Ph.D., 1978; D.h.c., Eindhoven Technical University. McCollum-Corcoran Professor and Professor, Caltech, 1998-. Chair, Division of Chemistry and Chemical Engineering, 1999-2009; Director, Beckman Institute, 2011-.

Eric Toberer, *Visiting Associate in Applied Physics and Materials Science*
B.S., Harvey Mudd College, 2002; Ph.D., University of California, Santa Barbara, 2006. Caltech, 2012-15.

Elitza I Tocheva, *Research Assistant Professor of Biology and Biological Engineering*
B.S., University of British Columbia, 2000; Ph.D., 2007. Caltech, 2013-15.

Ritsuko H (Hirai-Toner) Toner, *Lecturer in Japanese*
B.A., Kyoto University of Foreign Studies (Japan), 1974; M.A., University of Southern California, 1979; Ph.D., 1987. Caltech, 1992-2015.

Geoffrey C Toon, *Visiting Associate in Planetary Science*
B.A., University of Oxford, 1978; M.A., 1981; D.Phil., 1984. Research Scientist, Jet Propulsion Laboratory, 1986-. Caltech, 2001-15.

Frank Trentmann, Ph.D., *Moore Distinguished Scholar*
B.A., LSE, University of London, 1988; M.A., Harvard University, 1991, Ph.D., 1999. Caltech, 2014.

Maria Trnkova, *Lecturer in Mathematics*
M.A., Kazan State University, 2007; Ph.D., Palacky University, 2012. Caltech, 2014.

Sandra Troian, Ph.D., *Professor of Applied Physics, Aeronautics, and Mechanical Engineering*
B.A., Harvard University, 1980; M.S., Cornell University, 1984; Ph.D., 1987. Moore Distinguished Scholar, Caltech, 2004-05; Professor, 2006-.

Joel A Tropp, Ph.D., *Professor of Applied and Computational Mathematics*
B.A., B.S., University of Texas (Austin), 1999; M.S., 2001; Ph.D., 2004. Assistant Professor, Caltech, 2007-12; Professor, 2012-.

Pei-Yu Tsai, *Taussky-Todd Instructor in Mathematics*
B.A., National Taiwan University, 2008; M.A., Harvard University, 2011; Ph.D., 2013. Caltech, 2014-16.

Victor C Tsai, Ph.D., *Assistant Professor of Geophysics*
B.S., California Institute of Technology, 2004; A.M., Harvard University, 2006; Ph.D., 2009. Caltech, 2011-.

Doris Y Tsao, Ph.D., *Professor of Biology; Investigator, Howard Hughes Medical Institute*
B.S., Caltech, 1996; Ph.D., Harvard University, 2002. Assistant Professor, Caltech, 2008-2014; Professor, 2014-. Investigator, 2015-.

Hisashi Tsukamoto, *Visiting Associate in Applied Physics and Materials Science*
B.S., Kyoto University, Japan, 1979; Ph.D., University of Aberdeen, Scotland, 1999. Caltech, 203-15.

Carol C (Chace) Tydell, *Visiting Associate in Biology; Lecturer in Biology*
B.S., University of California (Davis), 1980; D.V.M., 1982. Adjunct Professor, Pasadena City College, 2007-. Visiting Associate, Caltech, 2007-09; Lecturer, 2008, 2010, 2011, 2012, 2013, 2014, 2015.

Christopher M (Chris) Umans, Ph.D., *Professor of Computer Science*
B.A., Williams College, 1996; Ph.D., University of California, 2000. Assistant Professor, Caltech, 2002-08; Associate Professor, 2008-10; Professor, 2010-.

Issachar Unna, *Visiting Associate in History*
Ph.D., Hebrew University, 1962. Caltech, 2014-17.

Edwin T Upchurch, *Visiting Associate in Astronomy*
B.S., University of Texas (Austin), 1964; M.S., University of Wisconsin (Madison), 1969; Ph.D., University of Texas (Austin), 1982. Staff Scientist, Jet Propulsion Laboratory, 2000-. Caltech, 2002-16.

Rolando Uribe, *Head Coach of Men's Soccer and Physical Education Instructor*
B.S., California State University (San Bernardino), 1995; M.S., 2002. Caltech, 2001-.

Faramarz Vafaee, *Harry Bateman Instructor in Mathematics*
Ph.D., Michigan State University, 2014. Caltech, 2014-17.

Kerry J Vahala, Ph.D., *Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics; Executive Officer for Applied Physics and Materials Science*
B.S., Caltech, 1980; M.S., 1981; Ph.D., 1985. Research Fellow in Applied Physics, 1985; Assistant Professor, 1986-90; Associate Professor, 1990-96; Professor, 1996-2002; Jenkins Professor, 2002-; Executive Officer, 2013-.

Palghat P Vaidyanathan, Ph.D., *Professor of Electrical Engineering*
B.Sc., University of Calcutta, 1974; B.Tech., 1977; M.Tech., 1979; Ph.D., University of California (Santa Barbara), 1982. Assistant Professor, Caltech, 1983-88; Associate Professor, 1988-93; Professor, 1993-. Executive Officer for Electrical Engineering, 2002-05.

Michele Vallisneri, *Visiting Associate in Physics Laurea,*
University of Parma (Italy), 1997; M.S., 2000; Ph.D., Caltech, 2002. Research Scientist, Jet Propulsion Laboratory, 2005-. Lecturer, Caltech, 2003-05; Visiting Associate, 2005-16.

John P Van Deusen, *Lecturer in Mechanical and Civil Engineering*
A.A., El Camino College, 1978; B.S., California State University (Long Beach), 2003. Caltech, 2004-15.

Jakob J van Zyl, *Senior Faculty Associate in Electrical Engineering and Aerospace; Lecturer in Electrical Engineering*
B.Eng., University of Stellenbosch (South Africa), 1979; M.S., Caltech, 1983; Ph.D., 1986. Research Fellow in Electrical Engineering, 1986; Lecturer in Electrical Engineering and Planetary Science, 2001-07; Faculty Associate, 2007-11, Lecturer, 2008-14; Senior Faculty Associate, 2012-16.

Michael C Vanier, *Lecturer in Computing and Mathematical Sciences*
B.S., McGill University, 1986; M.S., 1993; Ph.D., Caltech, 2001. Lecturer, 2004-15.

Aron Varga, *Visiting Associate inApplied Physics and Materials Science*
B.S., University of Cambridge, 2006; M.S., Massachusetts Institute of Technology, 2007; Ph.D., California Institute of Technology, 2013. Caltech, 2013-15.

Alexander J Varshavsky, Ph.D., *Howard and Gwen Laurie Smits Professor of Cell Biology*
B.S., Moscow State University, 1970; Ph.D., Institute of Molecular Biology, 1973. Caltech, 1992-.

Paulo Vasconcelos, *Visiting Associate in Geochemistry*
B.S., University of Kansas, 182; M.A., University of Texas, Austin, 1987; Ph.D., University of California, Berkeley, 1992. Caltech, 2011-16.

Tarciso A Velho, *Visiting Associate in Biology and Biological Engineering*
Ph.D., Oregon Health and Sciences University, 2008. Caltech, 2015-16.

Erik P Verlinde, *Visiting Associate in High Energy Physics*
Ph.D., University of Amsterdam, 1988. Caltech, 2015-16.

Michael A Vicic, *Lecturer in Chemical Engineering*
B.S., University of Akron, 1992; Ph.D., Caltech, 1999. Lecturer, 2003-08; 2010; 2012-15.

Thomas G Vidick, Ph.D., *Assistant Professor of Computing and Mathematical Sciences*
B.S., Ecole Normale Superieure, Paris, 2007; M.S., 2007; Ph.D., University of California, Berkeley, 2011. Caltech, 2014-.

Joaquin D Vieira, *Visiting Associate in Astronomy*
B.S., University of California, Los Angeles, 2002; M.S., University of Chicago, 2005; Ph.D., 2009. Caltech, 2013-15.

Tatiana G Vinogradova, *Visiting Associate in Aerospace*
M.S., Moscow University of Lomonosov, 1989; Ph.D., University of California, Los Angeles, 1999. Caltech, 2015-16.

Scott C Virgil, *Lecturer in Chemistry*
B.S., Caltech, 1987; Ph.D., Harvard University, 1991. Caltech, 2008; 2009: 2010; 2011; 2013; 2014; 2015.

Petr Vogel, *Senior Research Associate in Physics, Emeritus*
Ph.D., Joint Institute of Nuclear Research (USSR), 1966. Senior Research Fellow, Caltech, 1970-75; Research Associate, 1975-81; Senior Research Associate, 1981-2004; Lecturer, 1983-90; 1992; 1995-96; 1999-2000; 2006; Senior Research Associate Emeritus, 2004-.

Rochus E (Robbie) Vogt, Ph.D., *R. Stanton Avery Distinguished Service Professor and Professor of Physics, Emeritus*
S.M., University of Chicago, 1957; Ph.D., 1961. Assistant Professor, Caltech, 1962-65; Associate Professor, 1965-70; Professor, 1970-82; R. Stanton Avery Distinguished Service Professor, 1982-2002;R. Stanton Avery Distinguished Service Professor Emeritus, 2002-. Chief Scientist, Jet Propulsion Laboratory, 1977-78; Chairman, Division of Physics, Mathematics and Astronomy, 1978-83; Acting Director, Owens Valley Radio Observatory, 1980-81; Vice President and Provost, 1983-87; Director, Laser Interferometer Gravitational- wave Observatory Project, 1987-94.

David B Wales, Ph.D., *Professor of Mathematics, Emeritus*
B.S., University of British Columbia, 1961; M.A., 1962; Ph.D., Harvard University, 1967. Bateman Research Fellow, Caltech, 1967-68; Assistant Professor, 1968-71; Associate Professor, 1971-77; Professor, 1977-2008; Professor Emeritus, 2008-. Associate Dean of Students, 1976-80; Dean of Students, 1980-84; Executive Officer for Mathematics, 1985-91; Master of Student Houses, 1991-97.

Duane E Waliser, *Visiting Associate in Planetary Science*
B.S., Oregon State University, 1985; M.S., University of California (San Diego), 1987; Ph.D., 1992. Research Scientist, Jet Propulsion Laboratory, 2004-. Caltech, 2004-17.

Daifa Wang, *Visiting Associate in Electrical Engineering*
B.S., National Tsing Hua University, 2005; Ph.D., 2010. Caltech, 2014-15.

Shiing-wu Wang, *Lecturer in Accounting*
B.S., National Chiao Tung University, 1978; M.B.A., University of Wisconsin (Madison), 1980; Ph.D., University of Michigan, 1988. Associate Professor, University of Southern California, 1999-. Caltech, 2006-07; 2008-13; 2014-15.

Wei Wang, *Visiting Associate in Electrical Engineering*
Ph.D., Tsinghua University, 2005. Caltech, 2014-15.

Xiangyun Wang, *Lecturer in Chinese*
M.A., Central Institute for Nationalities (China), 1985; Ph.D., Harvard University, 1995. Caltech, 2001-15.

Zhen-Gang Wang, Ph.D., *Lawrence A. Hanson, Jr. Professor of Chemical Engineering*
B.Sc., Beijing University, 1982; Ph.D., University of Chicago, 1987. Assistant Professor, Caltech, 1991-97; Associate Professor, 1997-2002; Professor, 2002-15; Hanson Professor, 2015-.

Robert S Ward, *Piano Lecturer*
B.A., University of Illinois, 1962; M.A., 1964. Caltech, 2009-2015.

Gerald J Wasserburg, Ph.D., D.h.c., Sc.D.h.c., D.Sc.h.c., Dr.h.c., *Crafoord Laureate., John D. MacArthur Professor of Geology and Geophysics, Emeritus*
S.B., University of Chicago, 1951; S.M., 1952; Ph.D., 1954; D.h.c., University of Brussels; University of Paris; Sc.D.h.c., Arizona State University; D.Sc.h.c., University of Chicago; Dr.h.c., Rennes I University. Assistant Professor of Geology, Caltech, 1955-59; Associate Professor, 1959-62; Professor of Geology and Geophysics, 1963-82; MacArthur Professor, 1982-2001; MacArthur Professor Emeritus, 2001-.

Chairman, Division of Geological and Planetary Sciences, 1987-89; Executive Officer for Geochemistry, 1987-89.

Joel C Watson, *Visiting Associate in Economics*
B.A., University of California, San Diego, 1988; Ph.D., Stanford Graduate School of Business, 1992. Caltech, 2014-15.

Paul Webster, *Visiting Associate in Chemical Engineering*
B.S., Sheffield University, 1980; Ph.D., Brunel University. Caltech, 2013-16.

Sander Weinreb, *Senior Faculty Associate in Electrical Engineering*
B.S., Massachusetts Institute of Technology, 1958; Ph.D., 1963. Caltech, 1999-.

Alan J Weinstein, Ph.D., *Professor of Physics*
A.B., Harvard University, 1978; Ph.D., 1983. Assistant Professor, Caltech, 1988-95; Associate Professor, 1995-99; Professor, 2000-.

Cindy A Weinstein, Ph.D., *Professor of English; Vice Provost*
B.A., Brandeis University, 1982; Ph.D., University of California, 1989. Assistant Professor of Literature, Caltech, 1989-95; Associate Professor, 1995-2004; Associate Professor of English, 2004-05; Professor, 2005-; Executive Officer, 2008-14; Vice Provost, 2014-.

Paul S Weiss, *Visiting Associate in Applied Physics and Materials Science*
B.S., Massachusetts Institute of Technology, 1980; Ph.D., University of California, Berkeley, 1986. Caltech, 2015.

Stephan Weiss, *Lecturer in Mechanical and Civil Engineering*
B.S., Swiss Federal Institute of Technology, 2004; M.S., 2008; Ph.D., 2012; Caltech, 2015.

Daniel P (Dan) Weitekamp, Ph.D., *Professor of Chemical Physics*
B.A., Harvard College, 1974; Ph.D., University of California, 1982. Assistant Professor of Chemistry, Caltech, 1985-91; Associate Professor of Chemical Physics, 1991-2006; Professor, 2006-.

Xin Wen, *Visiting Associate in Chemistry*
B.S., Nanjing University, 1998; Ph.D., University of Rochester, 2005. Caltech, 2014-15.

Paul O Wennberg, Ph.D., *R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering; Executive Officer for Environmental Science and Engineering; Director, Ronald and Maxine Linde Center for Global Environmental Science*
B.A., Oberlin College, 1985; Ph.D., Harvard University, 1994. Associate Professor of Atmospheric Chemistry and Environmental Engineering Science, Caltech, 1998-2001; Professor, 2001-03; Professor of Atmospheric Chemistry and Environmental Science and Engineering, 2003-04; Avery Professor, 2004-; Director, Linde Center, 2008-11; Executive Officer, 2012-; Acting Director, Linde Center, 2012-14; Director, Linde Center, 2014-.

Brian P Wernicke, Ph.D., *Chandler Family Professor of Geology*
B.S., University of Southern California, 1978; Ph.D., Massachusetts Institute of Technology, 1982. Visiting Professor, Caltech, 1990; Professor of Geology, 1992-2001; Chandler Professor, 2001-.

Nicolas Wey-Gomez, Ph.D., *Professor of History*
B.A., Brandeis University, 1986; M.A., Johns Hopkins University, 1987; M.A., 1991; Ph.D., 1996. Associate Professor, Caltech, 2010; Professor, 2010-.

Ward Whaling, Ph.D., *Professor of Physics, Emeritus*
B.S., Rice University, 1944; M.A., 1947; Ph.D., 1949. Research Fellow, Caltech, 1949-52; Assistant Professor, 1952-58; Associate Professor, 1958-62; Professor, 1962-93; Professor Emeritus, 1993-.

Mark E Wiedenbeck, *Visiting Associate in Physics; Lecturer in Physics*
B.S., University of Michigan, 1971; Ph.D., 1978. Principal Research Scientist, Jet Propulsion Laboratory, 1992-. Visiting Associate, 2009-16; Lecturer, 2011.

Adam C Wierman, Ph.D., *Professor of Computer Science*
B.S., Carnegie Mellon University, 2001; M.S., 2004; Ph.D., 2007. Assistant Professor, Caltech, 2007-12; Professor, 2012-.

Kenneth Williford, *Visiting Associate in Aerospace*
B.S., University of the South, 1998; M.S., University of Washington, 2000; Ph.D., 2007. Caltech, 2013-16.

Josh Willis, *Visiting Associate in Environmental Science and Engineering*
B.S., University of Houston, 1996; M.S., University of California, San Diego, 1998; Ph.D, 2004. Caltech, 2014-16.

Richard M Wilson, Ph.D., *Professor of Mathematics, Emeritus*
B.S., Indiana University, 1966; M.S., Ohio State University, 1968; Ph.D., 1969. Sherman Fairchild Distinguished Scholar, Caltech, 1976; Professor, 1980-2014; Professor Emeritus, 2014-.

Erik Winfree, Ph.D., *Professor of Computer Science, Computation and Neural Systems, and Bioengineering*
B.S., University of Chicago, 1991; Ph.D.,

Caltech, 1998. Assistant Professor, 1999-2006; Associate Professor of Computer Science and Computation and Neural Systems, 2006-07; Associate Professor, 2007-10; Professor, 2010-.

Jay R Winkler, *Faculty Associate in Chemistry; Lecturer in Chemistry*
B.S., Stanford University, 1978; Ph.D., Caltech, 1984. Lecturer, 2002; 2004-05; 2009-10; 2013; 2014: Faculty Associate, 2008-17.

Kenneth J Winston, *Lecturer in Economics*
B.S., Caltech, 1973; M.S., 1974; Ph.D., Massachusetts Institute of Technology, 1979. Caltech, 2011; 2012; 2013; 2014; 2015.

Mark B Wise, Ph.D., *John A. McCone Professor of High Energy Physics*
B.Sc., University of Toronto, 1976; M.Sc., 1977; Ph.D., Stanford University, 1980. Assistant Professor of Theoretical Physics, Caltech, 1982-84; Associate Professor, 1984-85; Professor, 1985-92; McCone Professor, 1992-.

Pernilla Wittung, *Visiting Associate in Chemistry*
B.S., Chalmers University of Technology, Ph.D., 1996. Caltech, 2015.

Barbara J Wold, Ph.D., *Bren Professor of Molecular Biology*
B. S., Arizona State University (Tempe), 1973; Ph.D., Caltech, 1978. Research Fellow, 1978; Assistant Professor, 1981-88; Associate Professor, 1988-96; Professor, 1996-2002; Bren Professor, 2003-. Director, 2001-2011.

Joyce Y Wong, *Visiting Associate in Physics*
B.S., Caltech, 1995; M.S., 1996; Ph.D., 2000. Senior Research Scientist, Schlumberger, 2000-. Visiting Associate, Caltech, 2004-15.

Damien P Woods, *Senior Research Fellow in Computing and Mathematical Sciences*
B.S., National Universtiy of Ireland, Maynooth, 1999; Ph.D., 2005. Caltech, 2014-15.

James F Woodward, Ph.D., *J. O. and Juliette Koepfli Professor of the Humanities, Emeritus*
B.A., Carleton College, 1968; Ph.D., University of Texas (Austin), 1977. Mellon Postdoctoral Instructor, Caltech, 1983-86; Assistant Professor, 1986-88; Associate Professor, 1988-92; Professor, 1992-2001; Koepfli Professor, 2001-2010; Koepfli Professor Emeritus, 2010-. Executive Officer for the Humanities, 1992-95; 2000-2003.

Theodore Y Wu, Ph.D., *Professor of Engineering Science, Emeritus*
B. Sc., Chiao-Tung University (China), 1946; M.S., Iowa State University, 1948; Ph.D., Caltech, 1952. Research Fellow in Hydrodynamics, 1952-55; Assistant Professor of Applied Mechanics, 1955-57; Associate Professor, 1957-61; Professor, 1961-66; Professor of Engineering Science, 1966-96; Professor Emeritus, 1996-.

Peter J Wyllie, Ph.D., D.Sc.h.c., *Professor of Geology, Emeritus*
B.Sc. (Geology and Physics), Saint Andrews University (Scotland), 1952; B.Sc. (Geology), 1955; Ph.D., 1958; D.Sc.h.c., Saint Andrews University. Professor, Caltech, 1983-99; Professor Emeritus, 1999-. Chairman, Division of Geological and Planetary Sciences, 1983-87; Divisional Academic Officer, 1994-99.

Cheng Xiao, *Senior Research Fellow in Biology*
M.D., Xinjiang Medical University, 1996; M.S., West China University of Medical Sciences, 1999; Ph.D., Chinese Center for Disease Control and Prevention, 2002. Caltech, 2012-15.

Ming Xu, *Visiting Associate in Electrical Engineering*
B.S., Wuhan University of Technology, 2004; Ph.D., Zhejiang University, 2009. Caltech, 2014-15.

Yoshihiro Yamazaki, *Visiting Associate in Applied Physics and Materials Science*
B.S., Tohoku University, 1995; M.S., 1997; Ph.D., 2004. Caltech, 2011-16.

Changhuei Yang, Ph.D., *Professor of Electrical Engineering, Bioengineering, and Medical Engineering*
B.S. (Electrical Engineering); B.S. (Physics), Massachusetts Institute of Technology, 1997; M.S. (Engineering), 1997; B.S. (Mathematics), 2002; Ph.D., 2001. Assistant Professor of Electrical Engineering, Caltech, 2003-04; Assistant Professor of Electrical Engineering and Bioengineering, 2004-09; Associate Professor, 2009-10; Professor, 2010-.

Amnon Yariv, Ph.D., *Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering*
B.S., University of California, Berkeley, 1954; M.S., 1956; Ph.D., 1958. Associate Professor of Electrical Engineering, Caltech, 1964-66; Professor, 1966-74; Professor of Electrical Engineering and Applied Physics, 1974-79; Thomas G. Myers Professor of Electrical Engineering and Professor of Applied Physics, 1979-96; Summerfield Professor and Professor of Electrical Engineering, 1996-.

Leeat Yariv, Ph.D., *Professor of Economics*
B.Sc., Tel-Aviv University, 1992; M.Sc., 1995; M.A., Harvard University, 2001; Ph.D., 2001. Visiting Assistant Professor, Caltech, 2004-05; Associate Professor, 2005-10; Professor, 2010-.

Eylon Yavin, *Visiting Associate in Chemistry*
B.Sc., Herbrew University, 1994; M.Sc.,

Weizmann Institute of Science, 1997; Ph.D., 2002. Caltech, 2014.

Nai-Chang Yeh, Ph.D., *Professor of Physics; Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute*
B.S., National Taiwan University, 1983; Ph.D., Massachusetts Institute of Technology, 1988. Assistant Professor, Caltech, 1989-95; Associate Professor, 1995-97; Professor, 1997-; Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute, 2013-.

Yun Yen, *Visiting Associate in Chemical Engineering*
M.D., Taipei Medical College, 1982; Ph,.D., Thomas Jefferson University, 1987. Associate Cancer Center Director, City of Hope, 2005-. Caltech, 2007-15.

Yisong Yue, Ph.D., *Assistant Professor of Computing and Mathematical Sciences*
B.S., University of Illinois, 2005; Ph.D., Cornell University, 2010. Caltech, 2014-.

Mary A Yui, *Senior Research Associate in Biology*
B.S., University of California (Santa Barbara), 1977, M.S., Oregon State University, 1982; Ph.D., Florida University, 1995. Lecturer, Caltech, 2005; Senior Research Fellow, 2005-09; Caltech, 2009-15.

Yuk L Yung, Ph.D., *Smits Family Professor of Planetary Science; Jet Propulsion Laboratory Research Scientist*
B.S., University of California, 1969; Ph.D., Harvard University, 1974. Visiting Associate, Caltech, 1976; Assistant Professor, 1977-82; Associate Professor, 1982-86; Professor, 1986-2011; Smits Family Professor, 2012-; Jet Propulsion Laboratory Research Scientist, 2014-.

Roberto J Zenit Camacho, *Visiting Associate in Aerospace*
B.S., Universidad Nacional Autonoma de Mexico, 1992; M.S., California Institute of Technology, 1993; Ph.D., 1997. Caltech, 2014-15.

Ahmed H Zewail, Ph.D., D.Sc.h.c., D.h.c., D.Univ.h.c. D.Phil.h.c., D.H.L., LL.D.h.c., M.D.h.c., *Nobel Laureate., Linus Pauling Professor of Chemistry and Professor of Physics*
B.S., Alexandria University, 1967; M.S., 1969; Ph.D., University of Pennsylvania, 1974; D.Sc.h.c., American University of Cairo; Katholieke Universiteit Leuven; University of Pennsylvania; University of Lausanne; University of New Brunswick; Jadavpur University (India); Heriot-Watt University; Bogazici University; Ecole Normale Superieure; University of Oxford; University of Dublin; University of Cambridge; D.h.c., University of Rome; University of Liege; D.Univ.h.c.; Swinburne University of Technology (Australia); Peking University; Tohoku University; University of Buenos Aires; Babes-Bolyai University; D.Phil.h.c., Alexandria University; Lund University; D.H.L., American University of Beirut; LL.D.h.c., Concordia University (Canada); M.D.h.c., Pusan National University (Korea). Assistant Professor, Caltech, 1976-78; Associate Professor, 1978-82; Professor, 1982-89; Linus Pauling Professor of Chemical Physics, 1990-97; Professor of Physics, 1995-; Pauling Professor, 1997-.

Zhongwen Zhan, Ph.D., *Assistant Professor of Geophysics*
B.S., University of Science and Technology of China, 2006; M.S., 2008; Ph.D., California Institute of Technology, 2013. Caltech, 2015-.

Guanglian Zhang, *Visiting Associate in Mathematics*
Ph.D., Tsinghai University, 2004. Caltech, 2015.

Yingjun Zhang, *Visiting Associate in Electrical Engineering*
B.S., Fudan University, 2000; Ph.D., Hong Kong University of Science and Technology, 2004. Caltech, 2014.

Degang Zhao, *Visiting Associate in Applied Physics and Materials Science*
B.S., Shandong University, 2002, M.S. 2006; Ph.D., Chinese Academic Science, 2006. Caltech, 2014-15.

Dongping Zhong, *Visiting Associate in Chemistry*
M.S., Huazhong University of Science and Technology, 1988; M.S., Kansas State University, 1994; Ph.D., Caltech, 1999. Caltech, 2010; 2014-15.

Gang Zhou, *Sherman Fairchild Research Assistant Professor of Mathematics*
Ph.D., University of Toronto, 2007. Caltech, 2013-16.

Xinwen Zhu, Ph.D., *Associate Professor of Mathematics*
A.B., Peking University, 2004; Ph.D., University of California, Berkeley, 2009. Caltech, 2014-.

Kai G Zinn, Ph.D., *Professor of Biology*
B.A., University of California (San Diego), 1977; Ph.D., Harvard University, 1983. Assistant Professor, Caltech, 1989-95; Associate Professor, 1995-1999. Professor, 1999-.

Howard Zisser, *Visiting Associate in Chemistry*
B.S., University of Florida, 1985; Ph.D., John Hopkins University School of Medicine, 1989. Caltech, 2013-15.

Jonas Zmuidzinas, Ph.D., *Merle Kingsley Professor of Physics; Chief Technologist, Jet Propulsion Laboratory*
B.S., Caltech, 1981; Ph.D., University of California, 1987. Assistant Professor, Caltech,

1989-95; Associate Professor, 1995-2000; Professor 2000-10; Kingsley Professor, 2010-; Senior Research Scientist, 2005-11; Director, 2007-11; Jet Propulsion Laboratory Chief Technologist, 2011-.

Edwin Zschau, *Lecturer in Engineering*
B.A., Princeton University, 1961; M.B.A., Stanford University, 1963; M.S., 1964; Ph.D, 1967. Caltech, 2014, 2015.

INDEX

A

abbreviations of courses, 407
academic calendar, 4–5
academic divisions, 10, 289
academic standards, 184, 208, 309
accreditations, 50
administrative officers, 633
admission, 165, 168, 290
admission to candidacy, 170, 304, 305, 306
advanced placement, 167
advisers, 33, 181, 297
aerospace
courses, 406
graduate option, 319
instructional and research staff, 649–657
option representative, 289
study and research, 115
undergraduate minor, 227
Air Force ROTC, 179
allowance of credit, 188
Alumni Association, 40
Americans with Disabilities Act (ADA), 63
anthropology courses, 416
applied and computationalmath-ematics
courses, 418
graduate option, 324
instructional and research staff, 649–657
option representative, 289
study and research, 119
undergraduate option, 228
applied and computational math-ematics minor, 327
applied mechanics
courses, 422
graduate option, 327
instructional and research staff, 649–657
option representative, 289
study and research, 120
applied physics
courses, 424
graduate option, 331
instructional and research staff, 649–657
option representative, 289
study and research, 121
undergraduate option, 229
applying for admission, 165, 290
applying for financial aid, 195
applying for graduate standing, 290
Army ROTC, 179
art history courses, 429
ASCIT, 34
assistantships, 312
Associated Students of Caltech, 34
astronomical observatories, 123–124
astrophysics
courses, 433
graduate option, 336
instructional and research staff, 666–673
option representative, 289
study and research, 122
undergraduate option, 231
athletics, 33. See also physical education
auditing courses, 41
authorization and accreditation, 50
awards, 212, 314

B

bachelor of science degree, 184, 303
Beckman Auditorium, 22, 37
Beckman Institute, 24, 27
Beckman Laboratory, 19, 132. See also buildings and facilities

behavioral and social neurosci-ence
study and research, 124
graduate option, 340
option representative, 289

Big Bear Solar Observatory, 26
biochemistry and molecular biophysics
courses, 438
graduate option, 343
instructional and research staff, 644–648
option representative, 289
study and research, 125
bioengineering
courses, 440
graduate option, 344
instructional and research staff, 639–643
option representative, 289
study and research, 125
undergraduate option, 233
biology
advanced placement/college credit, 167
courses, 444
graduate option, 346
instructional and research staff, 639–643
option representative, 289
study and research, 128
undergraduate option, 236
board of trustees, 629
bookstore, 37
B.S./M.S. joint degree, 305
buildings and facilities, 19–27
business economics and management
courses, 457
undergraduate option, 240

C

café, 22, 27
calendar, 4–5
Cal Grants, 198
Caltech Center for Diversity (CCD), 29
Caltech-UCLA Medical Scientist Training Program, 351
Caltech-USC M.D./Ph.D. Program, 351
Caltech Y, 36
Cambridge Scholars program, 175, 205–206
campus directory, 7
candidacy, 187, 304, 305, 306, 307
career development, 38–40
Center for Data-Driven Discovery (CD3), 28, 674
Center for Teaching, Learning & Outreach (CTLO), 28
chemical engineering
courses, 460
graduate option, 352
instructional and research staff, 644–648
option representative, 289
study and research, 129
undergraduate option, 241
chemistry
advanced placement/college credit, 167
courses, 465
graduate option, 355
instructional and research staff, 644–648
option representative, 289
study and research, 131
undergraduate option, 244
Chinese. See language courses
civil engineering
courses, 475
graduate option, 360
instructional and research staff, 649–657
option representative, 289
study and research, 133
civil engineer's degree, 304
College Board Tests, 166, 169
college credit, 170
College Scholarship Service (CSS) PROFILE application, 195
committees, 635–638
computation and neural systems
courses, 478
graduate option, 364
instructional and research staff, 639–643
option representative, 289
study and research, 134

undergraduate concentration, 260, 261
computational science and engineering, 366
computer ethics, 53–55
computer science
courses, 482
graduate option, 367
instructional and research staff, 649–657
option representative, 289
study and research, 135
undergraduate option, 248
computer software agreement, 51
computer store, 37
computing support services, 674
conflict of interest and committment of graduate students, 299
conflicts of interest policy, 58
computing and mathematical sciences,
courses, 491
graduate option, 369
instructional and research staff, 649–657
option representative, 289
study and research, 137
contol and dynamical systems
courses, 493
graduate option, 370
instructional and research staff, 649–657
option representative, 289
study and research, 138
undergraduate minor, 251
controlled substances, 87–91
Copenhagen Scholars program, 173, 205–206
core curriculum requirements, 222
counseling service, 38
course loads. See overloads; underloads
courses, 406–627. See also under specific option
first-year schedule, 226
required for graduation, 221–225
credit, transfer of, 170, 188
credits, 43–45, 170, 188

D

deferral of entrance, 166
degrees
aeronautics, 321
bachelor of science, 170, 171, 180, 184, 186, 221 See also under specific option
civil engineer, 304
doctor of philosophy, 306. See also under specific option
electrical engineer, 304, 372
engineer, 304
joint B.S./M.S., 305
master of science, 303. See also under specific option
mechanical engineer, 390
space engineer, 321
departmental and option regulations, 185, 226–286, 319–405
detached duty, 301
dining facilities, 312
Direct Loan Programs, 197–204
directory of campus, 7
disputes, 52, 203. See also problem resolution
doctor of philosophy degree, 306. See also under specific option
dropping courses, 45, 180, 191
drugs on campus, 87–91
dual degree (3/2) plan, 171

E

early action application plan, 165
École Polytechnique Scholars Program, 174, 205
economics
courses, 495
undergraduate option, 252
Edinburgh Scholars program, 176, 205
electrical engineering
courses, 498
graduate option, 372

instructional and research staff, 649–657
option representative, 289
study and research, 139
undergraduate option, 254
electrical engineer's degree, 373
electronic information resources policy, 53
employment, 38–40, 68–70, 204–205
energy science and technology, 144, 508
engineering and applied science
instructional and research staff, 649–657
undergraduate option, 258
engineering courses (general), 509
engineer's degree, 304
English
advanced placement/college credit, 167
courses, 511
undergraduate minor, 262
undergraduate option, 262
English as a second language, 291, 521
English requirements for international students, 168–169, 290–291, 306
environmental science and engineering
courses, 522
graduate option, 375
instructional and research staff, 649–657
option representative, 290
study and research, 145
undergraduate concentration, 263
environment, health, and safety, 64
Equal Employment Opportunity, 68–70
essays for undergraduate admission, 166
examinations. See admission; placement examinations
exchange programs, 172, 292, 303, 324. See also study abroad
expenses, 205, 311. See also registration; tuition

F

facilities, 19–27
faculty advisers, 32, 297
faculty and officer listings, 676
faculty officers and committees, 635
faculty option representatives, 289–290
faculty-student relations, 33
FAFSA, 194
federal/state grants and loans, 198–204. See also financial aid; repayments
return of funds, 189–193
federal student aid application, 194
fees. See expenses
fellowships, 314
film courses, 527
financial aid, 193–212, 312–314
fire policy, 67
first-year course schedule, 226
foreign students, 41
French. See language courses
freshman advisers, 33
fresman seminars, 226, 528

G

GALCIT, 115
general deposit, 189, 192
geobiology. See geological and planetary sciences
geochemistry. See geological and planetary sciences
geological and planetary sciences
courses, 530
graduate option, 377
instructional and research staff, 658–661
minor, 270
option representative, 290

study and research, 148
undergraduate option, 264
geology. See geological and planetary sciences
geology summer field course, 193
geophysics. See geological and planetary sciences
German. See language courses
grade appeals, 45
grade-point average, 43
grades, 41–45
graduate degrees, 289–291, 303–310
graduate program,11
admission to, 303
career development advising, 38
expenses, 310–312
faculty advisers, 297
financial assistance, 312
housing, 311
option representatives, 289–290
options, 319–405
policies and procedures, 290–291
residency requirements, 292
graduate record examination, 305
graduate student council, 34
graduates, employment experience of, 40
graduate studies committee, 289
graduation requirements, 184–188, 222–225
grants, 192

H

harassment policy, 91
health services, 37–38
high school requirements for admission, 165
history
courses, 545
graduate minor, 382
undergraduate minor, 270
undergraduate option, 270
history and philosophy of science
courses, 555
graduate minor, 382
study and research, 150
undergraduate minor, 272
undergraduate option, 272
history of Caltech, 12
Hixon Writing Center, 29
honor system, 35, 51, 53, 168, 193, 291, 311
housing, 31, 188, 311
humanities, 150, 564
allowance of credit, 188
drop policy, 181
requirements, 223–224
instructional and research staff, 662–665

I

immigration matters, 41
interdisciplinary studies program, 151, 275, 568
Information Management Systems and Services (IMSS), 674
Information Science and Technology, 151, 568
Infrared Processing and Analysis Center (IPAC), 24, 124
Institute policies, 53
insurance, health, 37–38
interhouse activities, 34
international baccalaureate, 167
international students, 41, 290
employment program, 204
English requirement, 167, 290, 291, 302, 313, 321, 322, 338, 343, 375, 378
financial aid, 193
sabbaticals, 294
internships, 30–31
involuntary leave, 182, 296

J

Japanese. See language courses
Jet Propulsion Laboratory, 9, 12, 15, 26, 51, 87, 105, 116, 150, 159, 205, 298, 302, 674
joint B.S./M.S. degree, 304

K

Keck Observatory, 16, 27, 124, 159, 160
Kellogg Radiation Laboratory, 160. See also buildings and facilities
Kerckhoff Marine Laboratory, 129

L

laboratories, special, 302
laboratory of chemical synthesis, 132. See also buildings and facilities
laboratory requirements, 223
language courses, 568
late registration fees, 192, 293, 311
law courses, 572
leave, 181–182. See also sabbaticals
libraries, 29–30, 674
LIGO, 9, 27, 124, 159
literature. See English
loans, 199–204, 314
London Scholars program, 176, 205

M

major fields of study. See options
map of campus, 6
marine biology laboratory, 26, 129
master of science degree, 303, 309. See also under specific option
materials science
  courses, 573
  graduate option, 383
  instructional and research staff, 649–657
  option representative, 290
  study and research, 152
  undergraduate concentration, 260, 261
mathematics
  advanced placement/college credit, 167
    courses, 576
  graduate option, 387
  instructional and research staff, 666–673
  option representative, 290
  study and research, 153
  undergraduate option, 276
mechanical engineering
  courses, 585
  graduate option, 390
  instructional and research staff, 649–657
  option representative, 290
  study and research, 154
  undergraduate option, 278
mechanical engineer's degree, 304, 390
medical engineering
  courses, 591
  graduate option, 394
  instructional and research staff, 649–657
  option representative, 290
  study and research, 155
medical examination, 37. See also health services
medical school, 39, 351. See also premedical program
Melbourne Scholars program, 178, 205
menu classes, 222
microbiology, 156
missing student policy, 68
M.S. degree, 303. See also under specific option
mural policy, 68
music courses, 593

N

new student orientation, 168
Nobel laureates, 18
nondegree programs, 298
nondiscrimination policy, 68
neurobiology
  courses, 595
  graduate option, 397

instructional and research staff, 639–643
option representative, 290
study and research, 157
undergraduate option, 238

O

off-campus facilities, 26
officers and faculty listings, 676
officers of Caltech, 629, 633, 635
on-campus recruiting program, 39
option advisers, 33, 181, 186
option representatives, 289–290
options, 10–11
change of, 186
regulations, 185, 221–286, 319–405
selection of, 186
overloads, 187
Owens Valley Radio Observatory, 26, 124, 150, 160

P

Palomar Observatory, 26, 123, 159–160
part-time graduate study programs, 298
pass/fail grading, 41–45
patent agreement, 51
Pell grants, 198
performance courses, 596
performing and visual arts, 34
Ph.D. degree, 306. See also under specific option
philosophy
courses, 598
undergraduate minor, 281
undergraduate option, 281
physical education, 222, 602
physical examination, 37
physics
advanced placement/college credit, 168
courses, 608
graduate option, 398
instructional and research staff, 666–673
option representative, 290
study and research, 158
undergraduate option, 283
placement examinations
astrophysics, 336
physics, 400
planetary science. See geological and planetary sciences
policies of Caltech, 53
policy, conflicts of interest, 58
political science
courses, 617
undergraduate option, 285
postdoctoral scholars, 12
premedical program, 39, 237. See also medical school
prizes, 212, 314
problem resolution process, 50–51
PROFILE, 195–196
psychology courses, 619
publications, 35
public events, 37

R

recesses, 4–5
records and transcripts, 47–50
refunds, 189–193, 314
registration
general deposit, 189, 192
graduate students, 292
summer research, 181, 294
undergraduate students, 180
religious practice, 37
repayments, 189, 190–200, 314
research
areas of, 114–163
funds, 314
summer, 30, 181, 294
undergraduate, 30, 181
researchers, visiting, 292
residency requirements, 292
resolution process, 50–51
retention rates, 52
ROTC, 179

S

sabbaticals, 181, 294
SAT exams, 165, 166, 169
scholarships, 179, 197, 198, 212, 314
scholastic requirements, 184
scientific writing, 225
Scripps Institution of Oceanography, 303
seismological laboratory, 149
senior postdoctoral scholars, 12
sexual violence policy, 70
social science
  core institute requirements, 222–224
  courses, 621
  graduate option, 403
  instructional and research staff, 662–665
  option representative, 290
  study and research, 160
Spanish. See language courses
special students, 291–292
Spitzer Science Center, 25, 124, 159
Staff/Faculty Consultation Center, 675
staff of instruction and research, 639–673
Stafford Loan, 200
state and federal grants, 198
stipends, 312–314
structural mechanics
  undergraduate minor, 286
Student Activities Center, 32
Student Affairs, 675
student life, 31–37
  alcohol use, 87
  clubs, publications, and societies, 35–36
  employment, 38–40, 68, 204–205
  problem resolution procedure, 50
  health, 37–38
  housing, 31–32
Student Patent and Computer Software Agreement, 51
student records and transcripts, 47–50
study abroad, 172–179, 202
Submillimeter Observatory, 27, 124, 159, 160
substance abuse, 87
summer research, 30, 181, 294
Summer Undergraduate Research Fellowships (SURF), 30
systems biology
  graduate option, 345
  undergraduate option, 238
  study and research, 161

T

teaching assistantships, 312–313
tests. See admission; placement examinations
theses, 304, 305, 308
Title IX, 68, 171
3/2 dual degree plan, 171
transcripts, 44–50, 168, 183, 188, 191–193, 310–311
transfer admissions, 168
transfer of credit, 170, 188
trustees, 629
tuition, 188, 310

U

UCLA-Caltech Medical Scientist Training Program, 351
undergraduate program, 10
  admission, 164
  expenses, 188
  housing, 30
  options, 221–286
  requirements, 221–227
  research, 30, 227
undergraduate student events, 53
underloads, 187, 191, 211
units, 41
unpaid bills policy, 193, 310
USC-Caltech M.D./Ph.D. Program, 351

V

vacations. See recesses
veterans, 46
violence prevention, 107
visas, 41
visiting students, 177, 291, 292
visual arts, 35

W

whistleblower policy, 112
withdrawal, 180, 181, 182, 183–184
work-study, 38, 198, 204, 205, 207
writing, 167, 222, 223–224

Y

Y, Caltech, 36