Caltech

2019–2020 Catalog

2019–20

Caltech Catalog

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

September 2019

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.

Cover: Lance Hayashida

CONTENTS

Contents

ACADEMIC CALENDAR

2019-2020

First Term 2019

September 19–20
International student orientation

September 22–29
New student check-in and orientation for undergraduates

September 23–27
New student check-in and orientation for graduate students

September 26
Undergraduate Academic Standards and Honors Committee—1 p.m.

October 1
Beginning of instruction—8 a.m.

October 18
Last day for adding courses and removing conditions & incompletes

October 30–November 5
Midterm examination period

November 11
Midterm deficiency notices due—9 a.m.

November 13
Faculty meeting—noon to 1 p.m.

November 20
Last day for dropping courses, exercising pass/fail option, and changing sections

November 21–December 6
Registration for second term, 2019–20

November 28–29
Thanksgiving (Institute holiday)

December 6
• Last day of classes
• Last day to register for second term, 2019–20 without a $50 late fee

December 7-10
Study period

December 11*– 13
Final examinations, first term, 2019–20

December 13
End of first term, 2019–20

December 14–January 5
Winter recess

December 18
Instructors' final grade reports due—9 a.m.

December 25
Christmas (Institute holiday)

December 27, 30–31
Special release days and floating holiday

Second Term 2020

January 1
New Year's Day (Institute holiday)

January 6
Beginning of instruction—8 a.m.

January 7
Undergraduate Academic Standards and Honors Committee—9 a.m.

January 20
Martin Luther King Day (Institute holiday)

January 24
Last day for adding courses and removing conditions & incompletes

February 5–11
Midterm examination period

February 12
Faculty meeting—noon to 1 p.m.

February 17
Presidents' Day (Institute holiday)

February 18
Midterm deficiency notices due—9 a.m.

February 26
Last day for dropping courses, exercising pass/fail option, and changing sections

February 27–March 11
Registration for third term, 2019-20

March 11
• Last day of classes
• Last day to register for third term, 2019–20, without a $50 late fee

March 12–15
Study period

March 16*–18
Final examinations, second term, 2019–20

*First due date for final examinations

March 18
End of second term, 2019–20

March 19–29
Spring recess

March 23
Instructors' final grades due—9 a.m.

Third Term 2020

March 30
Beginning of instruction—8 a.m.

March 31
Undergraduate Academic Standards and Honors Committee—9 a.m.

April 17
Last day for adding courses and removing conditions and incompletes

April 29–May 5
Midterm examination period

May 11
• Midterm deficiency notices due—9 a.m.
• Last day for seniors to remove conditions and incompletes

May 15
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 20
Last day for dropping courses, exercising pass/fail option, and changing sections

May 21-June 5
Registration for first term, 2020–21, and for summer research

May 25
Memorial Day (Institute holiday)

May 29
• Last day of classes—seniors and graduate students
• Last day for presenting theses for the degrees of Doctor of Philosophy and Engineer

May 30–June 2
Study period for seniors and graduate students

June 3*–5
Final examinations for seniors and graduate students, third term, 2019–20

June 5
• Last day of classes—undergraduates
• Last day to register for first term, 2020–21, without a $50 late fee

June 6–9
Study period for undergraduates

June 8
Instructors' final grade reports due for seniors and graduate students—9 a.m

June 10
Curriculum Committee—10 a.m.
Faculty meeting—2 p.m.-3 p.m.

June 10*–12
Final examinations for undergraduates, third term, 2019-20

June 12
Commencement—10 a.m. End of third term, 2019–20

June 17
Instructors' final grades due for undergraduates—9 a.m.

June 24
Undergraduate Academic Standards and Honors Committee—9 a.m.

July 4-5
Independence Day (Institute holiday)

Summer Term 2020

June 15
Summer Term begins

September 1
Summer Term ends

September 7
Labor Day (Institute holiday)

First Term 2020–21
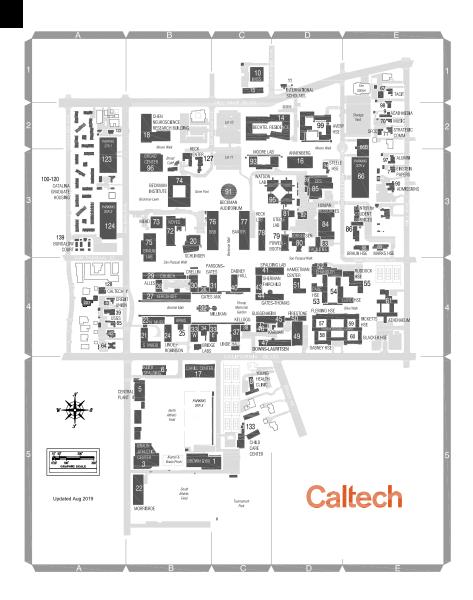
September 16–18
International student orientation

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 29
Beginning of instruction—8 a.m.

*First due date for final examinations

A B C D E

1

10
IMSS
15
11
INTERNATIONAL
SCHOLARS

Fire
Station
67 TACIT
98
9 ACAD·MEDIA
70 MUSIC
STRATEGIC
COMM

DEL MAR BLVD.

122

CHEN
NEUROSCIENCE
RESEARCH BUILDING

14
BECHTEL RESIDENCE

99

AVERY
HSE

Storage
Yard

SFCC 71

2

18

Lot 10

Moore Walk

KECK
CENTER
127

Broad
Café

Lot 11

MOORE LAB
93

ANNENBERG
16

Moore Walk

66b

STEELE
HSE

PARKING
STR 4

ALUMNI
97
7
EINSTEIN
PAPERS

PARKING
STR 1

123

BROAD
CENTER
96

66

90
ADMISSIONS

100-120
CATALINA
GRADUATE
HOUSING

BECKMAN
INSTITUTE

74

Gene Pool

WATSON
LAB

CES
85

HUMAN
RESOURCES

3

Beckman Lawn

91
BECKMAN
AUDITORIUM

95

81

82

84

CENTER for
STUDENT
SERVICES
86

PARKING
STR 2
124

MEAD 73

NOYES
72

76

BBB

77
BAXTER

KECK
LAB
78

STEELE
LAB
79
POWELL·
BOOTH

80

JORGENSEN
83
FACILITIES

BRAUN HSE

88

89

MARKS HSE

139
BUNGALOW
COURT

75
BRAUN
LAB

20

SCHLINGER

SAN PASQUAL ST.

San Pasqual Walk

San Pasqual Walk

4

128

CALTECH Y

63
CREDIT
UNION

39
USGS 65

42

64

29
ALLES
28
27 KERCKHOFF

CHURCH

CRELLIN

30

26

31

GATES ANX

Bechtel Mall

32

MILLIKAN

PARSONS·
GATES

40

Throop
Memorial
Garden

DABNEY
HALL

SPALDING LAB
41
SHERMAN
FAIRCHILD
43
44
GATES·THOMAS

HAMEETMAN
CENTER

51

52
CHANDLER

PAGE
HSE
53

54

RUDDOCK
HSE
55

LLOYD
HSE

Olive Walk

61

23 N MUDD

ARMS

KELLOGG

GUGGENHEIM
45

FIRESTONE
50

FLEMING HSE

RICKETTS
HSE

ATHENAEUM

21

24

25

33
W

34

33
E

37

38

46

KARMAN

49

57

59

BLACKER HSE

S MUDD

LINDE +
ROBINSON

BRIDGE
LABS

LINDE HALL

47
DOWNS·LAURITSEN

58

60

DABNEY HSE

CALIFORNIA BLVD.

5

KEITH
SPALDING
6

CAHILL CENTER
17

YOUNG
HEALTH
CLINIC
8

CENTRAL
PLANT

5

North
Athletic
Field

PARKING
STR 3

133

CHILD
CARE
CENTER

BRAUN
ATHLETIC
CENTER
3

Alumni &
Braun Pools

BROWN GYM 1

22

South
Athletic
Field

Tournament
Park

MORRISROE

GRAPHIC SCALE

Updated Aug 2019

Caltech

Campus Map

Caltech Campus Building Directory

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 Academic Media	9	E2
305 S Hill (Music House)	70	E2
315 S Hill (Strategic Comm. [front] SFCC [rear])	71	E2
315 S Wilson	122	A2
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
516 S Catalina Ave	221	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
Alles Laboratory	28	B4
Annenberg Center for Info Sci and Tech	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
Bechtel Residence	14	C2-D2
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
Building 15 (271 S Chester)	15	C1
Bungalow Court	139	A3
Cahill Center for Astroscience and Astrophysics	17	B5
Caltech Childcare Center	133	C5
Campus Housing Shop	135	A3
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
Chen Neuroscience Research Building	18	B2
Church Laboratory	29	B4
Downs-Lauritsen Laboratories	47	C4
Facilities	83	D3
Firestone Laboratory	50	D4
Fleming House	57	D4
Gates Annex	26	B4
Gates-Thomas Laboratory	44	C4
Guggenheim Laboratory	45	C4
Hameetman Center	51	D4
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 Laboratory	38	C4
Kerckhoff Annex	27A	B4
Kerckhoff Laboratories	27	B4
LIGO	69	D3
Linde Hall of Math and Physics	37	C4
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
Ramo Auditorium	77	C3
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
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	49	D4
Transportation & Grounds Operations	82	D3

General Information

INTRODUCTION

Caltech, founded in 1891, is a world-renowned science and engineering institute that marshals some of the world's brightest minds and most innovative tools to address fundamental scientific questions and pressing societal challenges.

Caltech is small in size, but prizes excellence and ambition. Its students receive an education that is notable for its rigorous curriculum, close collaborations with faculty, and small class sizes.

Students graduate from Caltech prepared to become world leaders in science, engineering, academia, industry, and public service. Graduates are well trained in their ability to identify, analyze, and solve challenging problems within and across science and engineering disciplines, and are prepared to apply and communicate their expertise broadly throughout their professional careers.

An independent, privately supported institution, Caltech also manages the Jet Propulsion Laboratory (JPL) for NASA, and Caltech also owns and operates the Seismological Laboratory, more than 50 research centers and institutes, and a global network of astronomical observatories, including the Palomar and W. M. Keck Observatories; the Institute also co-founded and co-manages the Laser Interferometer Gravitational-wave Observatory (LIGO).

The Institute's extraordinary faculty, students, postdoctoral scholars, and staff produce transformative breakthroughs in fields ranging from quantum science and engineering to bioinformatics and the nature of life itself, from human behavior and economics to energy and sustainability. Caltech faculty and alumni have earned national and international recognition, including 39 Nobel Prizes.

Caltech is also an integral part of Pasadena. Together with JPL, it is the city's largest employer and a source of programs that benefit the entire community.

To learn more about Caltech, visit www.caltech.edu/about.

HISTORICAL SKETCH

In September of 1891, Pasadena philanthropist Amos G. Throop (pronounced Troop) established Throop University, the institution that would eventually become Caltech.

Throop University opened its doors with 31 students and a six-member faculty. Throop might have remained simply a good local school had it not been for the arrival in Pasadena of astronomer George Ellery Hale. The first director of the Mount Wilson Observatory, Hale became a member of Throop's board of trustees in 1907, and began molding the school into a first-class institution for engineering and scientific research and education.

Hale would be joined later by chemist Arthur A. Noyes and physicist Robert A. Millikan. These three scholars set the school on the course it continues to follow to this day. By 1920, the school was renamed the California Institute of Technology, and the enroll-

ment 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 nearly 1,000 undergraduates, 1,200 graduate students, and some 300 professorial faculty and 700 postdoctoral scholars.

Caltech has more than 24,000 living alumni all over the world, many of them eminent in their fields of engineering, science, law, medicine, academia, and entrepreneurship.

Caltech's divisional structure, which began to coalesce in 1926, today comprises the Division of Biology and Biological Engineering (BBE); the Division of Chemistry and Chemical Engineering (CCE); the Division of Engineering and Applied Science (EAS); the Division of Geological and Planetary Sciences (GPS); the Division of the Humanities and Social Sciences (HSS); and the Division of Physics, Mathematics and Astronomy (PMA). To learn more about Caltech's history and the people behind the Institute's success, visit archives.caltech.edu.

EDUCATION AND RESEARCH

Students at Caltech work toward undergraduate and graduate degrees alongside their intellectual equals in an academic environment that emphasizes interdisciplinary teamwork, critical thinking, mutual support, and a deep understanding of core concepts and principles across fields.

Caltech students, faculty, and postdoctoral scholars are addressing fundamental scientific questions and pressing societal challenges. Together, they are expanding our understanding of the universe, shifting paradigms, launching new fields, and inventing the technologies of the future.

Caltech is home to more than 50 research centers and institutes. Some 90 percent of Caltech undergraduates participate in research during their time here.

UNDERGRADUATE PROGRAMS AND RESEARCH

Caltech offers undergraduates 28 majors (called "options") and 13 minors across the six academic divisions. The most popular options are computer science, chemical engineering, electrical engineering, mechanical engineering, and physics. Caltech also offers interdisciplinary programs in applied physics, biochemistry, bioengineering, computation and neural systems, control and dynamical systems, environmental science and engineering, geobiology and astrobiology, geochemistry, and planetary astronomy.

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 aca-

demic credit, and research for pay under a faculty member's grant or contract.

The senior thesis involves original research under the mentorship of a faculty member, an effort that develops research, writing, and presentation skills that together provide an excellent preparation for future graduate studies and/or professional life.

The 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. The work is carried out during a 10-week period in the summer, after which SURF students submit a written report describing the project, methods, and results of their work.

Most options offer undergraduate research courses in order to encourage research participation; students should consult listings and descriptions of opportunities.

Learn more about undergraduate programs and research at www.admissions.caltech.edu.

GRADUATE PROGRAMS AND RESEARCH

Students can enroll in Master of Science, Degree of Engineer, Doctor of Philosophy, BS/MS, and MD/PhD degree programs; the majority of graduate students are enrolled in the PhD program.

The academic work of the Institute is organized into six divisions: Biology and Biological Engineering (www.bbe.caltech.edu/); Chemistry and Chemical Engineering (www.cce.caltech.edu/); Engineering and Applied Science (www.eas.caltech.edu/); Geological and Planetary Sciences (www.gps.caltech.edu/); Humanities and Social Sciences (www.hss.caltech.edu/); and Physics, Mathematics and Astronomy (www.pma.caltech.edu/).

Graduate study at the Institute is divided further into a number of individual graduate options (degree programs), which are supervised by those professors whose interests and research are closely related to the area of the option. Entering graduate students are admitted into one of these options. The most popular options for graduate work are chemistry, physics, electrical engineering, and biology. Learn more at www.gradoffice.caltech.edu/.

ACADEMIC PARTNERSHIPS

Caltech maintains an array of external partnerships with other institutions in Southern California. These partnerships provide pre-med students with opportunities to work in area hospitals and train with practicing clinicians; allow students to participate in ROTC through a joint program with USC; and offer a 3/2 dual degree for students from 13 select liberal-arts colleges. Caltech undergraduate students can cross-register at Occidental College and Art

Center College of Design, and the Institute maintains relations with research partners such as the Scripps Institution of Oceanography at UCSD. Undergraduate students can also study abroad in Cambridge, Copenhagen, Edinburgh, London, Paris, or Melbourne during their junior or senior years. For graduate students, joint programs between Caltech and both the USC Keck School of Medicine and the UCLA David Geffen School of Medicine grant MD/PhD degrees.

FACULTY RESEARCH

The contributions of Caltech's faculty have earned national and international recognition. Caltech was elected to the Association of American Universities (AAU) in 1934 and remains a research university with "very high" research activity, primarily in STEM fields. Research is central to Caltech, and the Institute manages approximately $325 million in sponsored awards annually. Its largest federal funding agencies are the National Aeronautics Space Administration (NASA), National Science Foundation (NSF), Department of Health and Human Services, Department of Defense, and Department of Energy. Caltech faculty are highly productive in the fields of applied physics, astronomy and astrophysics, biology, biochemistry, biological engineering, chemical engineering, computer science, geology, mechanical engineering, and physics. More than 37 percent of faculty are members of the National Academy of Sciences, Engineering, and Medicine and/or are fellows of the American Academy of Arts and Sciences—the highest percentage of any faculty in the country with the exception of Rockefeller University. Caltech receives more invention disclosures per faculty member than any other university in the United States.

POSTDOCTORAL AND SENIOR POSTDOCTORAL SCHOLARS

More than 500 early-career scientists and engineers conduct research at Caltech as postdoctoral scholars. In addition, JPL 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.

RESEARCH CENTERS AND INSTITUTES

Research centers and institutes across campus bring together scientists and engineers to collaborate and add innovative and diverse perspectives to tackle society's most pressing challenges. Among those centers and institutes are:
- the Tianqiao and Chrissy Chen Institute for Neuroscience at

Caltech, which seeks to deepen our understanding of the
brain and how it works;

- the Beckman Institute, which develops methods, instrumentation, and materials for fundamental research in chemistry and biology;
- the Kavli Nanoscience Institute, which advances cross-disciplinary research in the areas of nanoscience and nanotechnology;
- the Donna and Benjamin M. Rosen Bioengineering Center, which encourages intensive, fruitful collaborations between bioengineering researchers;
- the Resnick Sustainability Institute, which fosters advances in energy science and technology through research, education, and communication;

Learn more about Caltech's research centers and institutes at www.caltech.edu/research/centers-institutes.

ON-CAMPUS ACADEMIC RESOURCES

Center for Teaching, Learning, & Outreach (CTLO)

The Center for Teaching, Learning, & Outreach (CTLO) supports Caltech's multifaceted educational efforts, including the design and instruction of undergraduate and graduate courses and curricula, formal and informal student learning, and educational outreach partnerships with K-12 teachers and students. With a commitment to evidence and innovation, CTLO focuses on:

Instructor Support: Supporting 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 discipline-based educational research.

Student Learning: Fostering opportunities for students to grow as teachers, mentors, and leaders. In addition to advising students on teaching and outreach-related projects, CTLO oversees the Caltech Project for Effective Teaching (CPET), a graduate student-led community offering seminars and Certificates of Interest and Practice in University Teaching, and collaborates with the undergraduate Academics and Research Committee (ARC) on course improvements, course ombuds, and other initiatives.

Educational Outreach: Helping faculty and students to develop K-12 outreach programs, including collaborations with schools and districts in Pasadena and Greater Los Angeles. CTLO assists faculty on grant proposals with educational components, convenes educational outreach coordinators from across Caltech's divisions, runs signature educational outreach programs for K-12 students and teachers during the summer and year-round, and serves as an interface for partner organizations offering K-12 opportunities at

Caltech.

Learn more at www.ctlo.caltech.edu.

Hixon Writing Center (HWC)

The Hixon Writing Center (HWC) 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 is funded in part by a generous donation from Alexander P. and Adelaide F. Hixon. The HWC is open during the academic school year. Learn more at www.writing.caltech.edu.

Libraries

The Caltech Library advances the Institute's mission to expand human knowledge by catalyzing information discovery and sharing. The Library maintains extensive research collections, a variety of study spaces, state-of-the-art knowledge management platforms, and a user-focused program of instruction and outreach.

The Sherman Fairchild Library (SFL) is the main library on campus. SFL is open every day until midnight and offers a range of collaborative and private study spaces including five bookable group study rooms and the TechLab, which houses several 3-D printers. Laptops, kindles, and electronic kits 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 service, DocuServe, is located on the first floor of SFL. Users can obtain books and articles not owned by Caltech Library at no charge and typically within 24 hours.

SFL is complemented by three branch libraries: Humanities and Social Sciences (Dabney), Astrophysics (Cahill), and Geology

(North Mudd). In addition, the Lookout, 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.

Visit the Library's website, www.library.caltech.edu, to access library collections and services or request research assistance from the Library.

Archives and Special Collections

The Caltech Archives and Special Collections facilitate understanding of the roles of Caltech and its faculty in the history of science and technology by collecting, organizing, preserving, and presenting the papers and other media that document the Institute's history. More than 300 manuscript collections include the personal and professional papers of 14 Nobel laureates and 14 National Medal of Science recipients. More than 10,000 of the photographs can be viewed online, and the Archives also maintains collections of artwork, rare books, and scientific instruments. These collections are all available to members of the Caltech community for educational and research purposes, as well as to qualified non-campus users. Contact the Archives at 626-395-2704 or archives@caltech.edu to arrange an appointment. More information, including finding aids for many of the collections, can be found at www.archives.caltech.edu.

JET PROPULSION LABORATORY

Founded by Caltech faculty in 1936 and located six miles from campus in La Cañada Flintridge, the Jet Propulsion Laboratory (JPL), which is managed by Caltech for NASA, is the leading U.S. center for robotic space exploration. JPL's 6,500 employees are tightly connected to the campus research mission and together enable the Institute to push the frontiers of space and Earth science. JPL is currently responsible for conducting NASA's missions for approximately two dozen spacecraft and 10 instruments employed in active missions, including the Mars Science Laboratory, Juno, Aquarius, GRAIL, and NuSTAR, all of which are pioneering new approaches for space exploration. Caltech and JPL engage in collaborations and joint appointments of faculty, lecturers, and visitors. Learn more at jpl.nasa.gov/.

STUDENT LIFE

UNDERGRADUATE STUDENT RESIDENCES

Seven of the undergraduate student residences are situated on either side 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 these seven residences is a separate unit with its own dining room and lounge, providing accommodations for between 65 and 100 students, depending on the facility. Each has its own elected officers; a long history of shared governance gives students a great deal of influence over their living environments. There are five undergraduate residential life coordinators (RLCs) in undergraduate campus housing, situated in different residences. 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 residences. Each residence has one or more RA, who are typically graduate students. 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 undergraduate residence and innovative residential complex was designed by Moore, Ruble, Yudell, and completed in September 1996. Located at the north end of the campus, Avery has an RLC, two RAs, 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 hosts programs and social events that facilitate involvement between residents and faculty in residence.

Bechtel Residence

Established in the fall of 2018 and located at the northeast edge of campus, the Bechtel Residence is the first residence to open on campus since 1996. With the opening of Bechtel, the Institute is able, for the first time, to provide on-campus housing to all undergraduates for the duration of their academic career. Bechtel is

named in honor of Caltech life trustee Stephen D. Bechtel, Jr., the founder of the S. D. Bechtel Foundation.

The 95,000-square-foot residence is a multigenerational residence open to all undergraduates with: 211 student bedrooms arranged as singles and in suites; six RA and one RLC apartments; and two faculty-in-residence apartments. Bechtel was intentionally designed to provide the community with the greatest flexibility in maximizing space as well as to encourage broader interaction, engagement, and residential life programming among residents. The facility includes three kitchens; eight common areas/study rooms; six laundry rooms; a 400-seat dining hall and servery; and support spaces.

STUDENT RESOURCES AND ACTIVITIES

Hameetman Center

The Hameetman Center, which opened in 2019, is a new campus center built on the site of the former Winnett Student Center. The Hameetman Center replaces Winnett as Caltech's central community gathering place. The 24,000-square-foot two-story center is named in honor of the Hameetman Foundation and Caltech trustee Fred Hameetman (BS '62) and his wife, Joyce, who provided the initial funding to initiate the design of the reimagined campus hub. It features a large public lounge, an expanded Red Door Marketplace, the Caltech Store, music rehearsal facilities, student club rooms, a multipurpose room, and a conference room. The rehearsal facility is made possible thanks to a gift from Emeritus Professor of Theoretical Physics Steven Frautschi and his wife, Mie.

Residential Experience

The Office of Residential Experience (ORE) has responsibility for the oversight of Caltech's residential programs, including programs carried out in the undergraduate houses, graduate student residences, and the Bechtel and Marks-Braun communities. The ORE works collaboratively with the Residential Life Coordinators, Resident Advisors, the Interhouse Committee, and other groups to ensure that student leaders in all our residential communities are trained and that there are programs in place to support their development. This is part of the shared governance that is central to the Caltech residential experience.

All residences and houses, including all their activities and programs, are expected to comply with Institute policies, Student Affairs policies, and the Caltech Code of Conduct. Potential Policy or Code of Conduct violations by a house or residence will be referred to the Caltech Routing committee. If the Routing Committee determines that the incident(s) is part of a Residential or House program or activity, it will be referred to ORE for further action. In this case, the Assistant Vice President for Student Affairs and Residential Experience (AVP) or her designee, will either (a)

manage the situation directly with the community so the concerns can be addressed, or (b) initiate an investigation into the incident. If an investigation is conducted, the investigators will report their findings to the AVP who will make a decision concerning whether any violations occurred and any consequences that may be imposed. The decision of the AVP may be appealed to the Vice President of Student Affairs within 10 days of the decision.

During the investigation, the AVP can suspend activities of the house or residence until further notice if deemed necessary for the health, safety, or the other benefit of the community. A range of outcomes may be considered as consequences to the house or residence if the group is found to have engaged in a policy violation. Possible sanctions including community education and/or suspension of the activity or event. Examples of events that warrant a response include an unregistered event or party, mistreatment of members, and hazing. If the potential situation also includes a potential policy violation involving an individual student(s), the student(s) will be referred to the appropriate Dean's office and may be subject to disciplinary action.

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 adviser 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 20 sports—10 each for men and women. All teams compete during a regular season, with many also competing or qualifying for the conference tournament in their respective sport. Individual scholar-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 a brand-new turf mixed-use baseball and soccer field, a second natural grass mixed-use field, an all-weather running track, eight tennis courts, and two 25-yard, eight-lane swimming pools. Indoor facilities include two full-size gymnasiums; four racquetball courts, two squash courts; a 5,000-square-foot weight room, satellite 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 helps to handle matters affecting the houses, in conjunction with staff from Student Affairs. 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 six elected officers, it is involved in many aspects of student life; oversees publication of *The Tech*, our undergraduate student newspaper; the *Big T* yearbook; a literary magazine called *Totem*; and the *Little t*, which provides lots of helpful information to incoming students. A directory, along with other student information, such as campus positions, links to the Interhouse Committee (IHC) and Academics and Research Committee (ARC), and other helpful information is available online at Donut.caltech.edu.

Besides overseeing 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, working closely with Student Activities and Programs part of the Office of Residential Experience. The student government is active in campus affairs. The student members of 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 to promote communication mainly around academic topics.

Graduate Student Council

The Graduate Student Council (GSC) is the student government for Caltech graduate students. It is the mission of the GSC to maximize the quality of life for the graduate student community at Caltech. The GSC Board of Directors interacts with the Institute's administrative bodies and is formed of subcommittees dedicated to academic support, advocating graduate student issues, sharing student news, and organizing social events.

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 representa-

tives, 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 their discretion, the Dean of Undergraduate Students, or their designee, may directly handle a matter also involving the Honor System, the Code of Conduct, and Institute Policies for undergraduate students.

The Honor System is also an important part of graduate student life. The dean of graduate studies is responsible for reviewing and making decisions concerning alleged honor code violations with respect to course-work. The Graduate Honor Council (GHC) serves as a consultative resource to the dean. At their discretion, the dean of graduate studies may request that the GHC investigate and hear a case, and provide its recommendations to the dean for final review and decision. 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 dean of graduate studies 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. Institute Policy violations 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, *Totem*; a student handbook, *the Little t,* which gives a survey of student activities and organizations and serves as a campus directory; a yearbook, *Big T*; an online undergraduate research opportunities handbook, *UROH;* and *Caltech Letters*, an online campus publication designed to let students talk about their research and their viewpoints on science with the broader world. 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

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 studio

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 Clubs

All student clubs must be officially recognized in order to be in and remain in good standing with the Institute. To become officially recognized, the club must annually apply for recognition. You will find details regarding this process outlined in the Student Club Handbook, which is available on the Office of Residential Experience website (ore.caltech.edu).

Once the club is officially recognized, it may plan on maintaining that recognition for the duration of the current academic year. The details of how to remain in good standing with the Institute are outlined in detail within the Student Club Handbook. These details include club oversight, privileges, responsibilities, finances, and other very important information. A recognized club will receive the following privileges: the ability to recruit members; advertise events; secure funding; conduct officer elections; provide trainings and use Institute facilities for meetings and events. Additional, key elements of club recognition include but are not limited to, having an advisor, an appropriate purpose, and a leadership infrastructure. Note that only recognized clubs will be allowed to participate in the annual Club Fair.

Clubs at Caltech are expected to follow Institute policy, Student Affairs policies, and the Caltech Code of Conduct. Potential policy or Code of Conduct violations by a club or in connection with a club event will be referred to the Assistant Vice President for Student Affairs and Residential Experience (AVP) or her designee, will either (a) manage the issue with the club through an appropriate Institute response, or (b) initiate an investigation into the incident. If an investigation is conducted, the investigators will report their findings to the AVP who will make a decision concerning whether any violations occurred and any consequences that may be imposed. The decision of the AVP may be appealed to the vice president of student affairs within 10 days of the decision.

During the investigation, the AVP may suspend the club's recognition and planned activities, if deemed necessary, for the health, safety, or other benefit of the community. A range of outcomes may be considered as consequences to the club if the group is found to have engaged in a policy violation. Possible sanctions examples include education, suspension of some or all of the group's privileges, or loss of their recognition status with the Institute. If the potential situation also includes a potential policy violation involving an individual student(s), the student(s) will be referred to the appropriate Dean's office and may be subject to disciplinary action.

Caltech Center for Diversity (CCD)

The Caltech Center for Diversity (CCD) mission is to provide education, advocacy, and allyship in order to increase institutional and personal capacity for diversity and ensure a community committed to equity and inclusive excellence. We create and implement campus-wide initiatives and programs that will increase the knowledge, skills, and attitudes for all members of the Caltech community to thrive in a diverse world.

Awareness and Education. We are committed to building the capacity for cultural competencies, skills, and action by designing workshops and trainings appropriate for all constituents on campus. We value consistent assessment and formative feedback to facilitate sustainable and lasting change.

Advocacy through Collaboration. We actively engage with the Caltech community to promote and provide access to information and resources that help achieve our academic and personal goals. The CCD provides programs and services to meet the specific needs of racially underrepresented groups, women, all sexual and gender identities (LGBTQ+), underserved, and ally communities on campus.

Allyship. We create spaces and skill building opportunities for all members of the community to engage with issues related to their multiple identities. We provide resources and promote an environment that is supportive for all.

If you are interested in getting involved with CCD, please check the center website: www.diversitycenter.caltech.edu.

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 Observation

Caltech has a quiet room for prayer, mediation, quiet reflection and religious observation. The quiet room is located in the Hameetman Student Center. For information about religious clubs, see the Student Clubs website at ore.caltech.edu.

Special Meals

If you have a dietary restriction that requires a special request, please contact Caltech Dining Services at dining@caltech.edu. If your restriction rises to the level of a disability, please visit the CASS website at http://www.cass.caltech.edu/ to request accommodation.

Registration for Student Sponsored Events:

Student events, including parties, activities, and programs that are hosted by a house or residence, are a privilege at Caltech and are part of the social framework of the Institute, but must be conducted in a safe and legally compliant manner. We expect the student body to follow laws, polices, guidelines for events, use common sense, and good judgement. All events that meet the following criteria must be registered: Events or activities of a club, organization or houses with:

1. 50 or more people present without alcohol
2. 15 or more people where alcohol is present—these events require a third-party bartender
3. Off-campus event where Institute funds are used
4. Construction or Chemicals will be used

Student Auxiliary Services

The Student Auxiliary Services, Gift & Technology Store (http://caltechstore.caltech.edu) is located on the first floor of the new Hameetman Center. Established in the 2018–2019 academic year with a lead gift from The Hameetman Foundation, the Hameetman Center (formerly the Winnett Student Center) is now renamed in the Foundation's and Fred Hameetman (BS '62) and his wife, Joyce's honor. Owned and operated by the Institute, the store serves the students, faculty, and staff, carrying a stock of Caltech authors' books, insignia merchandise, gift items, school supplies, computer hardware, and accessories that support Caltech's educational and research mission. Also located on the first floor of the new Hameetman Center is the redesigned Red Door Marketplace that offers freshly brewed coffee and tea, full menu, and bakery items.

STUDENT WELLNESS SERVICES

GENERAL INFORMATION

Student Wellness Services is committed to supporting the health and emotional well-being of Caltech students. Through individualized treatment planning, consultation, and outreach, we provide direct services and community-level interventions to improve student wellness and allow students to focus on their pursuit of academic success and holistic development. All enrolled students,

regardless of insurance coverage, are eligible for basic medical and psychological care, crisis counseling, and occupational therapy at Student Wellness Services, through payment of the health fee. Students who require specialty or longer-term care beyond the scope of what Student Health Services provides will be referred to community providers using their health insurance; costs associated with this care are the responsibility of the student.

A full description of the range of services and programs offered by Student Wellness Services can be found at http://wellness.caltech.edu.

HEALTH FORMS

Prior to initial registration, each admitted student is *required* to submit entrance health forms that include medical and immunization history. Information regarding immunization requirements and the completion of the health forms are posted on the New and Prospective Student website (http://wellness.caltech.edu/resources/new-students). Matriculating students will receive access to the Student Health Portal to enable secure online upload of the forms. Health forms must be received no later than August 15, 2019. Failure to meet this requirement will result in a registration hold, and students will be unable to register for winter term classes until clearance is complete.

STUDENT HEALTH INSURANCE

Students have the option to waive the Caltech student insurance plan (United HealthCare Student Resources) during the waiver period each year, provided they show proof of adequate alternative coverage. Students will be automatically enrolled in the Caltech plan if a waiver is not submitted. The Caltech plan provides coverage (with deductible and copay) for most hospital and surgical costs, as well as the cost of outpatient treatment for injury, illness, and psychotherapy. Students must be enrolled in order to maintain eligibility for coverage. Students on an approved medical leave can continue coverage for up to one year; the cost of the plan premiums will be the responsibility of the student. Complete coverage and exclusion details can be found here: benefits.caltech.edu/health/students/medical. If the Caltech plan has been waived, students are advised to ensure that their alternative coverage provides access to medical and mental health providers close to campus.

CALTECH CARE TEAM

GENERAL INFORMATION

The CARE Team is a multidisciplinary group of professional staff from key areas of the Institute. Each member brings knowledge and expertise in their field, including mental health, crisis intervention, student development, staff consultation, campus security, academic support, and residential life. The CARE Team also collaborates with many other entities across campus including athletics, the Equity Office and Title IX, the Center for Diversity, Student Faculty Programs, International Student Programs, and the academic divisions.

The CARE Team connects students with resources and support. Through early identification of academic difficulties, social concerns, behavioral disruptions, and health issues, the CARE Team can partner with students to create individualized plans to help mitigate crises and promote success. The behaviors listed below, especially when more than one are present, may be signs of distress:

- Mood or behavior changes
- Changes in personal hygiene
- Social withdrawal
- Excessive absences from class or lab
- Persistent disinterest or disengagement in work
- Escalated substance use
- Talking about death, dying, or suicide
- Disruptive and/or aggressive behavior
- Threatening language or social media postings

The CARE Team will collaborate with the referring party to create a support plan, which may include outreach, academic or personal counseling, referral to campus support services, and other relevant resources.

Referrals to the CARE Team can be made at: caltechcares. caltech.edu

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 strate-

gies. 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 (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 adviser 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 are arranged 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, postdoctoral scholars, and alumni are welcome 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 Handshake for students seeking full-time or work-study employment. 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 213.)

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 Handshake, the CDC online job listing resource. Students may wish to confer with the summer internship 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, Caltech surveys graduating students' future plans. Over several years, approximately 35 percent of graduating seniors immediately pursue graduate study, primarily PhD programs, 55 percent pursue full-time employment, 10 percent have not accepted offers yet, and 10 percent pursue other options, such as a creating a start-up, fellowships for graduate study abroad, travel, or additional study in order to enter a new area of interest, etc.

At the M.S. degree level, about 90 percent continue in graduate school, and the remainder accept employment. Of those receiving the Ph.D. degree, about 60 percent accept postdoctoral, faculty, or other academic/research positions, about 40 percent pursue positions in areas such as national laboratories, industry, STEM teaching, public policy, etc.

CALTECH ALUMNI ASSOCIATION

The mission of the Caltech Alumni Association (CAA) is to promote the interests of Caltech as a world standard of academic excellence by strengthening the ties of goodwill and communication between the Institute, its alumni, and its students, and by maintaining programs to serve their needs.

The Caltech Alumni Association empowers students and alumni to connect with each other and build meaningful professional relationships through CAA programs, events, and networking platforms. Alumni are encouraged to share with current students their experiences and wisdom gained since graduating from Caltech.

We welcome all students to the CAA as future alumni and are proud to grant CAA membership to all new alumni upon graduation.

The Caltech Alumni House is located at 345 South Hill Ave, Pasadena CA, 91106. Learn about our programs for students and alumni and get involved at 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 affiliated with 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.

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. Grades other than E, I and W are assumed to be based on work completed and evaluated at the time of grade submission.

E and I Grades

E Grades. 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. In addition, students should be aware that E grades can impact ability to meet eligibility requirements. If an E grade impacts a student's academic standing, the grade may be due by the first day of classes. See section Scholastic Requirements for additional information.

If a student receives an E and does not complete the work by the date specified by the instructor or by Add Day (or a different date specified by the instructor), 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.

E Count Limitations. 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.

I Grades. 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. In addition, students should be aware that I grades can impact ability to meet eligibility requirements.

If an I grade impacts a student's academic standing, the grade may be due by the first day of classes. See section Scholastic Requirements for additional information.

Students receiving grades of E or I should consult with their instructors, and one of the deans, at the time of issue regarding 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. In the absence of an earlier deadline, 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. Waiving of this one year rule is done in only the most exceptional of circumstances and 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.

Petitions and Exceptions

Once recorded, a grade will only be changed 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. Timely submission of petitions is encouraged. The usual criterion for a late drop is documentation that the student in fact discontinued submitting assignments and exams in that course before Drop Day, but did not file a timely drop request. 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.

Petitions from graduating seniors submitted later than the first UASH meeting following graduation (which normally takes place shortly after graduation) will not be accepted for consideration, except to correct an error by the Institute.

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.

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.

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 freshmen by an admissions committee or, for students whose status after the first year is uncertain, by the Undergraduate Academic Standards 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 requirements imposed by the student's option, two elective courses in which he or she is to be graded on a pass/fail basis if the course 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 Drop Day. 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 (this does not include those courses taken in the first two terms freshmen year or those designated pass/fail by the instructor, option, or curriculum committee).

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, grades, as well as other educational records. 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. 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 education records nor any personally-identifiable information contained therein, other than directory information (see below), may be made available to anyone else, other than the student, without the consent of the student. Where the student consents to disclosure of personally-identifiable information from the student's education records and Caltech chooses to disclose such information, if the student so requests, the Institute will provide the student with a copy of the records disclosed. The Institute will maintain a record of each request for access to and each disclosure of personally-identifiable information from the education records of a student, as required by applicable federal law or regulation.

2. Students are allowed access to their educational records as follows: A student may inspect and review his or her academic transcript during normal working hours. To inspect and review 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 designees, as appropriate. A mutually-convenient time will be arranged within 45 days after receipt of the request for the student to inspect and review 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. If circumstances effectively prevent the student from exercising their right to review their education records, the Institute will make other arrangements. 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 designees, decide not to amend the record as requested, the student will be informed of the decision and of his or her right to a hearing. The student will have, on request, an opportunity 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. To request a hearing, the student must submit a written request to the vice president for student affairs or his or her designee. 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 will amend the record accordingly, and inform the student of the amendment 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 will 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. If the Institute places a statement in the education records of the student, the Institute will maintain the statement with the contested part of the record for as long as the record is maintained and will disclose the statement whenever it discloses the portion of the record to which the statement relates.

3. The Institute considers the following to be directory information: a student's name, UID, addresses (permanent, campus and local/off-campus, and email), 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. 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 in writing 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, he or she may contact the registrar for more information.

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.

PARENT, GUARDIAN, AND EMERGENCY CONTACT NOTIFICATION POLICY

Caltech understands and supports a student's right to confidentiality regarding educational records[1] as well as matters related to a student's experience at the Institute. Most communications from Caltech regarding academics, health and safety, advising, enrollment, and policies are directed only to students. However, the Institute does encourage students to share important information with their parent(s) or guardian. Subject to the allowable

exceptions under FERPA, there may be circumstances under which a Caltech administrator makes the determination that notification to parent(s) or a guardian is indicated, and notification may be made without a student's consent. In most cases, when a Caltech administrator determines that involving parent(s) or guardian is necessary, the student will be given an opportunity to make contact in advance of the administrator's communication. Administrators will consider any relevant information which may indicate that notification to parent(s) or guardian may not be appropriate based on individual circumstances. The Institute expects all students to designate an emergency contact who is a parent or guardian or other family member who may be notified in order to address a health or safety emergency, and who is in a position to make decisions on the student's behalf in the case of a medical emergency. An alternate emergency contact also may be identified for other purposes.

Situations that may warrant the involvement of a student's, parent(s), guardian, or emergency contact may include, but are not limited to:

1. *Concerns about a student under the age of 18.*
   Caltech administrators will initiate communication with the parent(s) or guardian of a minor student in the cases described below, as well as any other concerns about a minor student that may benefit from collaboration with the student's support system.
2. *Change in enrollment or status of an undergraduate student.*
   A change in the enrollment status of an undergraduate student may occur as a result of disciplinary action, unsatisfactory academic progress, or other factors. If an undergraduate student is separated from the Institute, the parent(s) or guardian will be notified by mail at the permanent address on file.
3. *Medical emergencies.*
   State law prohibits health care professionals from disclosing medical information to the parents or guardian of a student without the student's explicit consent. In the event a student is incapacitated, unable to communicate, or otherwise cannot make decisions on their own behalf, the Institute will first cooperate with medical providers and then notify the emergency contact, parent(s) or guardian on file as soon as possible.
4. *Unexplained absence from campus.*
   If it comes to the attention of Caltech administrators that a student is inexplicably absent from campus for more than 24 hours, or there is reason to believe that a student missing for fewer than 24 hours and is in danger, the emergency contact, parent(s) or guardian will be contacted in order to aid in

locating the student. Caltech has a Missing Student Policy that guides the response of the Institute and cooperation with law enforcement and other officials.

5. Significant disruption to the campus community.

The emergency contact, parent(s) or guardian of a student may be notified if the student is behaving in a way that is substantially disruptive to the campus community, there is reason to believe the student is at risk of harming themselves or others, or is placed under arrest or charged with a crime related to conduct on campus.

6. Repeated or flagrant violations of the Substance Abuse Policy.

Caltech administrators may contact parent(s) or guardian if a student under the age of 21 is found responsible for serious or repeated violations of Institute policy related to the possession, use or distribution of alcohol or drugs. Consideration in these situations will be given to the following conditions: the violation involved harm or threat of harm to self, others or property; the violation involved an arrest in which the student was taken into custody; the violation resulted in or could result in the student being suspended and/or removed from an Institute residence; the student has shown a pattern of violations; the student required urgent medical intervention as a result of consumption of alcohol and/or drugs.

7. Student death.

In the event of a student death, Caltech administrators will cooperate with law enforcement, the coroner, medical personnel, and any other relevant officials who will provide official notification to the deceased student's next of kin.

There may be additional, unforeseen circumstances when we believe it is in the best interest of the student to notify a parent or guardian. We reserve the right to act in such cases on our own best judgment, framed within the approach to emergency contact and parental/guardian notification stated above.

[1]*The Family Educational Rights and Privacy Act (FERPA) (20 U.S.C. § 1232g; 34 CFR Part 99)*

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. program 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, which do not fall within the jurisdiction of other Policies or the Honor System, 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, residential life coordinators, 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 led to an acceptable resolution.

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

A facilitator 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 or their designee. The decision of the vice president or designee is final.

If a 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 WASC Senior College and University Commission (WSCUC) at www.wscuc.org/comments. WASC is the academic accrediting body for Caltech. An individual may contact the Bureau for Private Postsecondary Education (BPPE) for review of a complaint. BPPE may be contacted at 2535 Capitol Oaks Drive, Suite 400, Sacramento, CA 95833, website: www.bppe.ca.gov; tele-

phone: (916) 431-6959; 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 royalty-free, nonexclusive license to use such computer software and written work for purposes for or on behalf of the 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 235 freshmen enrolled during the 2017-18 academic year, 230 reenrolled in the first term of the 2018-19 academic year and are progressing, yielding a persistence rate of 98 percent after all allowable exclusions. Of the 264 freshmen enrolled during the 2012-13 academic year, 242 graduated by June 2018, 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 229 entering graduate students enrolled in a Ph.D. program during the 2017-18 academic year, 223 reenrolled in the first term of the 2018-19 academic year and are making satisfactory academic progress, resulting in a persistence rate of 97 percent. Of the 16 entering graduate students enrolled in M.S. programs during the 2017-18 academic year, 6 earned a terminal M.S. degree within one year, while two were admitted into the Ph.D. program.

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 activities are an important part of campus life. Students are required to follow Event Planning Procedures: studentaffairs.caltech.edu/policies.

CODE OF CONDUCT

THE CALTECH COMMUNITY'S STATEMENT ON ETHICAL CONDUCT

We are all part of the Caltech community whether we are located on campus, at JPL, at observatories or anywhere else in the universe. As members of the Caltech community, we expect that each of us will embody the high standards that have gained Caltech its worldwide reputation. In 2012, members representing the Caltech community began a conversation on ethical conduct. These discussions focused on the overarching values of our community. As a result of these discussions, we describe, in detail, these values in 11 short statements.

1. Strive for Excellence
- We commit to excellence in all things in process as well as outcomes, knowing that only the process is truly under our control.
- Responsibility and accountability are the hallmarks of our
- community.

2. Act with Integrity
- We uphold integrity in all we do.
- We hold ourselves accountable for the outcomes of our actions.

3. Encourage Open, Honest, and Respectful Discourse
- We encourage open, honest, and respectful discourse from and between all members of the community, regardless of position, length of service, or role.
- We treat one another with civility.

4. Respect and Promote Freedom of Inquiry
- We encourage curiosity in research, scholarship, and exploration, and we create the conditions where inquiry can flourish.

5. Foster a Supportive and Diverse Community
- Every member of the Caltech community treats one another with dignity and respect.
- We value different perspectives, opinions, and ideas.

- We enable one another's excellence.
- We support the health and wellness of all community members.

6. Commit to Education
- The opportunity for excellence in education exists at all levels and in formal and informal ways that benefit students, employees, and members of our community.
- We are committed to being great educators—as leaders, mentors, and friends—not only of our students, but also of our community, our peers and colleagues, and ourselves.

7. Conduct Work Responsibly
- We fulfill the obligations of our role.
- We are responsible stewards of the Institute resources entrusted to us, including the environment, equipment and facilities, money and people.
- We respect the environment and are conscious of our impact.

8. Protect the Interests of Those Who Place Their Trust in Us
- We are forthright with our students, their parents, employees, managers, and people who rely on us for leadership and accountability at all levels.
- We hold ourselves to the highest standards of integrity in peer reviews, scientific evaluations, and recommendations.
- We represent ourselves accurately and factually to our peers, sponsors, and the general public.
- We are open and honest in all our dealings with the government, external agencies, taxpayers, and donors.
- We honor our obligations to donors and sponsors.

9. Provide and Maintain a Safe Environment for Learning and Working
- We create, provide, and maintain a safe environment for ourselves and for others.
- We foster the physical, mental, and emotional well-being of our community.

10. Obey the Law and Comply with Institutional Policies
- We are scrupulous in all business dealings.
- We are truthful, forthright and accurate when preparing all books, records, documents, reports, and publications.
- We adhere to local, state, and federal laws and regulations.
- We deal honestly with government in all matters.

11. Represent Caltech
- We represent Caltech whether we are based on campus, at JPL, our observatories, or anywhere else in the world.

- We are ambassadors and advocates, embodying the high standards that we set for ourselves and to which we are held by others.
- We are committed to the Institute and its mission recognizing that our actions as individuals reflect on Caltech.

As members of the Caltech community, we embrace the letter and the spirit of these principles. Each member is personally responsible for incorporating these principles into their own actions and is encouraged to speak up if they, in good faith, believe the Institute or any individual is falling short of living up to them. We are proud of Caltech and to share the community's commitment to these values.

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, cellular phones and related services) to assist members of the Caltech 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 Caltech and of faculty, staff, students, and other members of the Caltech 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 Caltech, although some incidental personal use is permitted. Faculty, staff, students, and other members of the Caltech community ("users") who use Caltech's electronic information resources should be guided by the Caltech Code of Conduct. Passwords issued to users are for their use only and are not to be shared with others. Users assume responsibility for the appropriate use of Caltech's electronic information resources and agree to comply with all relevant Caltech policies and all applicable local, state, and federal laws. Examples of inappropriate or unauthorized use of Caltech'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 Caltech policy;

- destruction of or damage to equipment, software, or data belonging to others;
- disruption or unauthorized monitoring of electronic communications;
- interference with use of Caltech 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 Caltech's tax-exempt status and, therefore, violates Caltech 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 copyrighted files;
- violations of privacy;
- academic dishonesty;
- sending chain mail;
- spamming;
- downloading, viewing, and/or sharing of materials in violation of Caltech's policy regarding Unlawful Harassment, including Gender-Based Misconduct (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.

Caltech will apply this policy consistent with applicable requirements under Federal and State law and its obligations under the European Union General Data Protection Regulation with respect to protection of personal data of individuals located in the European Union. 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 Caltech property and users should not have an expectation of privacy with respect to their use of these resources or any of the data, files, or other records generated by, stored or maintained on them. Password capabilities and other authentication measures 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 Caltech with respect

to personal messages or files stored on electronic information resources owned and managed by Caltech.

While Caltech does not routinely examine the content of electronic mail messages or otherwise monitor individual usage, it does routinely monitor the normal operation of computing and networking resources, including network activity patterns, system logs, general and individual usage patterns, and other indicia necessary to ensure the integrity and stability of its electronic information resources. Caltech will investigate suspected abuse, misuse, or compromise of its resources, systems and services.

Caltech typically does not access 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 any such messages, data, files, and records at any time without prior notification. Any such action will be taken for reasons Caltech, 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 Caltech policies and the law; and locating electronic messages, data, files, or other records related to these purposes. Users must therefore understand that any electronic messages, data, files, and other records generated by, stored, or maintained on Caltech electronic information resources may be electronically accessed, reconstructed, or retrieved by Caltech even after they have been deleted.

Caltech 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 and other academic personnel; (2) by the Vice President of Administration and Chief Financial Officer for staff and postdoctoral scholars at campus or the JPL Director for Human Resources for employees and postdoctoral scholars 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 is unavailable for a timely response, the General Counsel may authorize access.

In conclusion, the use of Caltech electronic information resources is a privilege, not a right, and Caltech may revoke this privilege or decline to extend this privilege at any time. Inappropriate use of Caltech resources may result in administrative discipline up to and including separation from Caltech. Suspected illegal acts involving Caltech 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 Caltech's electronic information resources or relevant Caltech policies should be directed to the Provost, the General Counsel, the Chief Information Officer, the Associate Vice President for Human Resources, the JPL Director for Human Resources, the Dean of Undergraduate Students, or the Dean of Graduate Studies.

COMPLIANCE WITH EXPORT LAWS AND 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 Caltech 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 Caltech'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 Caltech to civil sanctions and criminal penalties.

It is the responsibility of Caltech faculty and staff to ensure Caltech'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 Compliance Office staff at (626) 395-2641 or export@caltech.edu.

CONFLICTS OF INTEREST POLICY

1.0 Policy

The mission of 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 Caltech. 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 its trustees, officers, senior management, faculty, students, postdoctoral scholars, 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 Caltech 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 Caltech's trustees, officers, faculty, postdoctoral scholars, 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 Caltech, 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 Caltech. Caltech faculty, staff and postdoctoral scholars are

required to complete Caltech's Conflict of Interest Disclosure form on an annual basis and to submit changes or additions within 30 days of a new interest, activity or change.

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.

2.0 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 Caltech. It is important, however, that all employees make timely disclosure of any such conflict of interest. Each employee should apply their 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:

2.1 Each employee has a duty to act in the best interest of Caltech and avoid actions that would call into question the integrity of the employee or Caltech.

2.2 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 Caltech, should not act on behalf of Caltech in any transaction involving that interest. No employee should participate in the selection, award, or administration of a contract with any party with whom they are negotiating regarding potential employment or any arrangement concerning potential employment.

2.3 An employee should avoid outside activity involving obligations which may conflict or appear to conflict with Institute interests, including its interest in the employee's full- or part-time services (i.e. a conflict of commitment). Outside employment, directorships, consulting or similar arrangements, must

be disclosed. Conflicts will be reviewed by the Division Chair for faculty, the supervisor and the Associate Vice President for Human Resources for campus staff and postdoctoral scholars and the JPL Ethics office for JPL staff. Campus and JPL staff and postdoctoral scholars are required to obtain approval prior to engaging in outside activities. Campus and JPL staff must complete the Request for Outside Activity form as required in Personnel Memorandum PM 9-3.

2.4 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, their official decisions or actions on Institute matters.

2.5 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 they could use or might appear to have the opportunity to use, for personal gain, confidential information or special knowledge gained as a result of their relationship with Caltech.

2.6 An employee should refrain from unauthorized disclosure of non-public information concerning Caltech. Additionally, an employee should not use non-public information accessed through the performance of a government contract for personal gain.

2.7 No employee should make unauthorized use of Caltech resources for their personal benefit or for the benefit of any other person. Incidental personal use of resources is authorized by Caltech. See Institute Policy on Acceptable Use of Electronic Information Resources and "JPL Rules!".

2.8 It is sound practice to discourage gifts and favors from people with whom Caltech 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.

2.9 Any employee doing business on behalf of Caltech 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.

2.10 No employee should act in any Institute matter involving a member of their immediate family including, but not limited to, matters affecting family members' employment or evaluation or advancement in Caltech. Immediate family includes an employee's spouse or domestic partner and chil-

dren. The employment of relatives as that term is defined in Personnel Memorandum (PM 9), is subject to the conditions and restrictions described in PM 9, including the requirement to complete the Nepotism Evaluation process whenever a relative of an employee is considered for employment in the same organization as the employee.

Any employee who believes that their 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 Campus Hotline at 626-395-8787 or submitting a hotline form. JPL employees should consult Laboratory requirements, and seek guidance and/or report possible conflicts of interest by contacting the JPL Ethics Office.

3.0 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 Caltech'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 Caltech requires that the member perform their responsibilities to Caltech and appropriately use their 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, Caltech relies on its faculty to be alert to the possible effect of outside activities on the integrity of their decisions and on their ability to fulfill their obligations to Caltech. Accordingly, in addition to the conflict rules set forth above, the following guidance is provided for faculty:

3.1 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 member 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.

3.2 Disclosure 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 postdoctoral 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 or postdoctoral scholar must also sign the written disclosure to signify understanding of the issues involved.

3.3 Disclosure 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.

3.4 Disclosure is mandatory 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.

4.0 Conflict of Interest Requirements Imposed by Federal Sponsors

The National Science Foundation (NSF) and Public Health Service (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.

5.0 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 Caltech may be compromised because of an external financial or business relationship held by Caltech that may bring financial gain to Caltech.

5.1 Identifying Institutional Conflicts of Interest

Caltech 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 eco-

nomic 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 Caltech might consider to be appropriate. Any activity, financial and/or operational, that may bring into question Caltech'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:

> 5.1.1 Significant gifts to Caltech 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.

> 5.1.2 The acquisition of goods and services for Caltech represents a large portion of Caltech's expenditures. Purchasing goods and services from companies that sponsor research at Caltech, or who are licensees of Institute technology, may raise issues similar to those raised by large gifts from commercial sponsors.

> 5.1.3 A potential institutional conflict of interest exists simply by Caltech 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.

5.2 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 Administration and CFO 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 Hotline at 626-395-8787 or the JPL Ethics Office at 818-354-6338 or submitting a hotline form.

DISABILITY AND REASONABLE ACCOMMODATION

1.0 Policy

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

As required by law, Caltech will make reasonable accommodations to otherwise qualified individuals with known disabilities including students, faculty, postdoctoral scholars, staff, volunteers, interns and job applicants to ensure equal employment opportunities and equal access to Caltech educational programs, services, activities and facilities unless doing so would constitute an undue hardship or a fundamental alteration. Caltech also will provide reasonable accommodations to employees with pregnancy-related conditions consistent with federal and state law.

Caltech also, as appropriate, will conduct a fair, timely, and thorough investigation into complaints within the scope of this Policy to determine what occurred and take reasonable steps to remedy the effects of any discrimination and prevent recurrence of the behavior. Caltech provides all parties with appropriate due process and reaches reasonable conclusions based on the evidence collected. Caltech takes appropriate action, including disciplinary measures, when warranted.

2.0 ADA Coordinators

The following individuals have been designated to coordinate Caltech's efforts to comply with and carry out Caltech's responsibilities under applicable disability laws and Caltech policy (ADA Coordinators). Individuals who believe they have been discriminated against based on their disability or who wish to request an accommodation should contact the appropriate Caltech ADA Coordinator.

ADA Coordinators for Undergraduate and Graduate Students:

Lesley Nye, 626-395-6351
Associate Dean of Undergraduate Students

Katheryn G. (Kate) McAnulty, 626-395-6346
Associate Dean for Graduate Studies

ADA Coordinator for Faculty:
  Stacey Scoville, 626-395-6320
  Administrator to the Provost
  ADA Coordinator for Staff and Postdoctoral Scholars

Campus
  Rose Murillo, 626-395-5930
  Disability and Leave Manager

JPL
  Veronica Jarquin, 818-354-6146
  Human Resources Consultant

3.0 Reasonable Accommodations

Caltech will provide reasonable accommodations that are appropriate and consistent with legal requirements. In evaluating requests for accommodations, Caltech will engage in a timely and good faith interactive process with the requesting individual to determine what, if any, accommodations should be provided. Caltech has the right to request documentation supporting an accommodation request, including documentation of the disability, when the disability or the need for accommodation is not obvious.

4.0 Right to File a Grievance

An individual who believes they have been the subject of disability discrimination may file a grievance. In addition, after engaging in the interactive process and after Caltech has determined whether a reasonable accommodation is available, an individual requesting an accommodation who disagrees with the decision, may file a grievance. Grievance procedures may be obtained from the appropriate ADA Coordinator.

5.0 Right to File Complaint with Outside Agency

Employees and applicants may also 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). Complaints may also be directed to the Bureau for Private Postsecondary Education at http://bppe.ca.gov.

Related Policies and Procedures:
   •   Nondiscrimination and Equal Employment Opportunity
   •   Unlawful Harassment
   •   Procedures Regarding Unlawful Harassment

ENVIRONMENT, HEALTH, AND SAFETY

1.0 Policy

Caltech including its division the Jet Propulsion Laboratory ("JPL"), is committed to conducting activities in a manner that promotes the safety and health of faculty, staff, postdoctoral scholars, students, and visitors, applies sound practices in environmental stewardship 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 faculty, staff, postdoctoral scholars, students, and visitors at Caltech.
- Faculty, supervisors and managers are responsible for establishing good environmental, health and safety practices in their laboratories, classrooms and workplaces and for providing safe equipment and facilities for faculty, staff, postdoctoral scholars, students, and visitors.
- All faculty, staff, postdoctoral scholars, students and visitors are expected to keep themselves informed of conditions affecting their health and safety, participate in safety training, follow proper environmental, health and safety policies and procedures, and report accidents and potentially unsafe or illegal conditions or practices promptly to their supervisor or manager or other appropriate office.
- Caltech activities must comply with all applicable federal, state, and local environmental, health and safety laws and regulations.

2.0 Roles and Responsibilities

Caltech has the responsibility to establish environmental, health and safety policies and procedures and provide resources to ensure compliance with environmental and safety laws. Caltech performs these functions through the following committees and administrative and management structure:

2.1 Institute Environment, Health and Safety Committee

Caltech's Environment, Health and Safety Committee ("IEHSC") is responsible for recommending campus-wide environmental, health and safety policies to the President.

The IEHSC is responsible for making recommendations regarding the allocation of Institute resources so as to maintain environmental (e.g., air emissions, soil contamination, water discharges, hazardous waste management) and workplace health and safety compliance. In addition, the committee monitors developments through the campus Environment, Health, and Safety Office to ensure that

Institute policies are observed, remain current, and are consistent with the anticipated changes in regulatory requirements.

2.2 Campus Environment, Health, and Safety Office

The Environment, Health, and Safety Office ("EHS"), which reports to the Associate Vice President for Facilities, is responsible for providing technical, regulatory, and related-advisory services to the campus community. EHS works in partnership with the academic divisions and administrative departments to develop and implement safety programs that provide technical guidance and training support relevant to the operations of the laboratories and 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 environmental, health and safety policies and procedures. EHS also initiates site reviews to assess potential hazards and determine effective controls, and coordinates hazardous waste training and hazardous waste disposal. EHS, working closely with the Office of the General Counsel, reviews legislation, recommends policies, provides regulatory agencies with required data and reports, and investigates and reports environmental, health and safety incidents.

2.3 Campus Division Chairs and Department Heads

The Caltech campus consists of divisions conducting research and educational activities, and administrative departments supporting the operations of Caltech. It is the responsibility of each division chair and department head to ensure that their units conduct operations in accordance with applicable laws and regulations and implement Caltech's environmental, health and safety policies and procedures. Division chairs and department heads maintain responsibility for day-to-day management and implementation of their environmental, health and safety programs.

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

2.4 JPL Office of Safety and Mission Success

The Office of Safety and Mission Success at JPL ("JPL OSMS") establishes and leads the Environmental, Health and Safety and Mission Assurance Programs for projects, programs and major tasks. JPL OSMS appropriately manages risks and enhances the probability of mission safety

and success. In this capacity, JPL OSMS is an independent organization, reporting directly to the JPL Director. JPL OSMS continually assesses risk and provides infrastructure to ensure that JPL maintains compliance with the JPL Prime Contract and applicable federal, state and local environmental, health and safety requirements. JPL OSMS applies knowledge, innovation and independence to achieve successful missions that inspire the world while safeguarding JPL's people, assets and reputation.

2.5 JPL Environmental, Health and Safety Program Management

The JPL Occupational Safety Program Office, the JPL Systems Safety Program Office and the JPL Environmental Affairs Program Office are chartered with establishing and leading programs related to occupational safety, systems safety and environmental compliance, respectively, and are tasked with appropriately managing risks and enhancing the probability of mission safety and success. These JPL program offices, working closely with the Office of the General Counsel, review legislation, recommend policies, provide regulatory agencies with required data and reports, and investigate and report environmental, health and safety incidents. Each of the environmental, health and safety program management offices has office-specific policies that are detailed in JPL Rules!

2.6 Campus and JPL Manager and Supervisor Responsibilities

All managers and supervisors, both academic and administrative, at campus and JPL, are responsible for conducting operations in accordance with all applicable laws and regulations and Caltech policies, practices and programs.

Managers are responsible for ensuring that areas under their management have adequate resources for environmental, health and safety programs, practices and equipment. Managers are also responsible to ensure that those areas under their management are in compliance with Caltech's environmental, health and safety policies, practices and programs.

Supervisors, including Principal Investigators ("PIs"), with guidance and assistance from the environmental, health and safety offices listed above, are responsible for implementing environmental, health and safety policies, practices and programs, ensuring that workplaces, including laboratories and equipment, are safe and well-maintained, training and informing employees, students, and visitors about workplace-specific hazards and safety procedures, providing personal protective equipment, correcting violations, investigating incidents and complaints, overseeing proper storage and disposal of hazardous materials, enforcing policies (including appropriately disciplining employees and students who vio-

late environmental and safety requirements), and appropriately documenting activities and processes.

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

2.7 All faculty, staff and students

All faculty, staff, postdoctoral scholars and students at campus and JPL are responsible for:

- Keeping themselves informed of conditions affecting their health and safety,
- Participating in safety training programs as required by the governing organization's policy and their supervisors,
- Performing work in a safe and prudent manner,
- Adhering to health and safety practices in their workplaces, classrooms, and laboratories, and
- Advising of or reporting potentially unsafe practices, illegal activities or serious hazards in the workplace, classroom or laboratory, and cooperatively participating in the investigation and/or remediation of any incidents.

The success of Caltech's environmental, health and safety management activities requires the active involvement of individuals through participation in training, compliance with established environmental, health and safety procedures, and reporting hazards and potential violations.

It is the responsibility of all faculty, staff, postdoctoral scholars and students at Caltech to disclose fully any activity that may result in a violation of environmental, health or safety laws or regulations, and to cooperatively participate in the investigation and remediation of any incidents.

2.8 Visitors and Contractors

Visitors and those who do business with Caltech either at Campus or JPL, such as contractors, consultants and vendors, are responsible for performing their work in a manner that protects Caltech from environmental, health and safety risks and complies with all applicable federal, state and local laws and regulations and all applicable environmental, health and safety policies, practices and programs.

3.0 Reporting

In matters of actual or potential regulatory enforcement action, investigations, or employee complaints, the appropriate environmental, health and safety office will work closely with the Office of the General Counsel to coordinate Caltech's response to external regulatory agencies concerned with workplace health, safety, and environmental compliance.

Any questions or concerns regarding compliance should be brought to the attention of the appropriate manager or supervisor or to the appropriate environmental, health and safety office. Alternatively, concerns can be raised with the appropriate division chair or vice president at campus, or the OSMS Director at JPL. In addition, concerns can be raised anonymously for campus through the anonymous hotline (626) 395-8787 or (888) 395-8787 or online at Caltech Hotline or, for JPL, through the anonymous hotline (818) 393-6483, or the NASA Safety Reporting System.

4.0 Sanctions

Caltech expects all faculty, staff, postdoctoral scholars and students to be vigilant in complying with all environmental, health and safety requirements and to properly conduct their activities at Caltech.

Local, state and federal laws and regulations establish civil and criminal penalties for violations of environmental, health and safety laws and regulations, including substantial fines and possible imprisonment.

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 up to and including termination of employment or involuntary leave/expulsion from Caltech.

GENDER-BASED MISCONDUCT

1.0   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. It is the policy of Caltech to provide a work and academic environment free of unlawful discrimination, harassment and sexual misconduct. Caltech will not tolerate such conduct and is committed to educating the community in ways to prevent its occurrence.

This policy prohibits all forms of sexual or gender-based discrimination, harassment and sexual misconduct (Gender-based Misconduct), including sexual assault, non-consensual sexual contact, relationship violence, sexual exploitation, and stalking (Prohibited Conduct). Caltech also prohibits retaliation against an individual who reports, submits a complaint, or who otherwise participates in good faith in any matter related to this policy.

Caltech will take prompt and equitable action upon receiving a report of Prohibited Conduct to determine what occurred and will take reasonable steps to stop and remedy the effects of any such conduct and prevent its recurrence. Caltech provides all parties with appropriate due process and will reach reasonable

conclusions based on the evidence collected. Caltech will take appropriate action, including disciplinary measures, when warranted, up to and including termination of employment or changes to student enrollment status, including permanent separation from the Institute.

2.0   Scope

This policy applies to all current students, faculty, supervisory and nonsupervisory staff, postdoctoral scholars, volunteers, interns, vendors, independent contractors, persons performing services under contract with the Institute, visitors, and any other individuals regularly or temporarily employed, studying, living, visiting, or otherwise participating in Caltech's educational programs or activities.

This policy applies to Prohibited Conduct occurring on Institute-controlled property, at Institute-sponsored events, in-Institute programs or activities, by Institute affiliated organizations and off-campus where the conduct has continuing adverse effects on any member of the Caltech community in any Caltech program or activity.

Members of the Caltech community are encouraged to promptly report Prohibited Conduct to Caltech or consult with a confidential resource, regardless of where the incident occurred, or who committed it. An individual who has experienced sexual misconduct is encouraged to immediately seek assistance from a medical provider and report the incident to local law enforcement. Reports to Caltech and law enforcement may be pursued simultaneously.

Even if Caltech does not have jurisdiction over the person accused of Prohibited Conduct, Caltech will still take prompt action to provide for the safety and well-being of the individual reporting and the campus community, including taking reasonable steps to stop and remedy the effects of the Prohibited Conduct and to prevent recurrence of the behavior.

When used in this policy and accompanying procedures, complainant refers to the individual who reportedly is the subject of the Prohibited Conduct and respondent refers to the individual who is reported to have engaged in the Prohibited Conduct.

In the event an act of discrimination is not simply about an individual, but has broader implications, including affiliation with a student organization, this policy will also apply. No student organization or residential facility may discriminate against anyone in the Caltech community based on a protected characteristic.

3.0 Prohibited Conduct

Sexual and gender-based discrimination, harassment and sexual misconduct violate Title VII of the Civil Rights Act of 1964, as amended, Title IX of the Education Code, and California law. All forms of such conduct are prohibited under this policy, including

sexual or gender-based discrimination, sexual or gender-based harassment, and sexual misconduct, including sexual assault, non-consensual sexual contact, relationship violence, sexual exploitation and stalking (Prohibited Conduct). Reported behavior that does not constitute Prohibited Conduct under this policy, but is nevertheless determined to be inappropriate pursuant to another applicable Caltech policy, may subject a responding party to disciplinary action.

All individuals are protected against Prohibited Conduct regardless of gender, sexual orientation, gender identity or gender expression. Prohibited Conduct can be committed by individuals of any gender, regardless of an individual's gender identity, gender expression, or sexual orientation, 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. Organizations affiliated with the Institute or that use Caltech property or resources in connection with their activities also are prohibited from engaging in Prohibited Conduct.

Attempts or threats to commit Prohibited Conduct are equally covered by this policy.

3.1 Sex or Gender-Based Discrimination refers to unfavorable treatment based on sex, sexual orientation, gender identity, or gender expression.

The following are examples of conduct that may constitute sexual or gender-based discrimination:
- Denying an employee a promotion because they are gay or straight.
- Rejecting a student from house membership because they are transgender.
- Limiting membership in a student club or activity to members of one sex.

3.2 Sexual or Gender-Based Harassment

3.2.1 Sexual Harassment is unwelcome sexual advances, requests for sexual favors, and other conduct of a sexual nature when:
Quid Pro Quo: Submission to such conduct is made either explicitly or implicitly a term or condition of an individual's employment or education or submission to or rejection of such conduct is used as the basis for decisions affecting that individual's employment or academic terms or status; or
Hostile Environment: Such conduct unreasonably interferes with an individual's work or academic performance or creates an intimidating, hostile, or offensive work or academic environment. An individual may experience sexual harassment even if the offensive conduct was not aimed directly at them.

3.2.2 Gender-Based Harassment is harassment based on an individual's actual or perceived sex, gender, gender identity or gender expression including harassing or bullying conduct based on the individual's gender expression, gender identity, transgender status, gender transition, or nonconformity with sex stereotypes.

A single isolated incident may create a hostile environment if the incident is sufficiently severe, particularly if the conduct is physical. For example, a single incident of unwanted physical conduct of a sexual nature, like grabbing an intimate body part, may be sufficiently severe to constitute a hostile environment. Behavior of a harassing nature that does not rise to the level of unlawful harassment but is nevertheless determined to be inappropriate may subject the offender to disciplinary action.

The following are examples of conduct that, depending on the nature, frequency and severity, may constitute sexual or gender-based harassment:

- Sending unwanted sexually-oriented jokes to a student or work group email list.
- Displaying explicit sexual pictures in common areas of Institute housing or on a work computer station where others can view it.
- Making or using derogatory comments, epithets, slurs, or jokes of a gender-based or sexual nature.
- Ostracizing individuals from group activities because of their sex, gender or gender identity, gender expression, sexual orientation or because they objected to harassing behavior.
- Making unwelcome graphic comments about an individual's body, using sexually degrading words to describe an individual.
- Engaging in unwanted suggestive or obscene communications.
- Engaging in unwelcome touching, fondling or groping of a sexual nature.
- Making unwanted sexual advances.
- Promising a benefit to someone in exchange for engaging in sexual activity.
- Exposing one's genitals to another without consent.

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 similarly-situated individuals, who are not in the consensual relationship, less favorably. Caltech practice, as well as more general ethical principles, prohibits individuals from participating in 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 regarding those

individuals. Sexual or romantic relationships between an undergraduate student and a faculty, postdoctoral scholar or staff member are not permitted.

Upon learning about a relationship that violates this policy, 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 to a claim of sexual harassment. The individual in the relationship with greater power will be held responsible.

3.3 Sexual Misconduct

Prohibited sexual misconduct includes sexual conduct that occurs by force or threat of force or without affirmative consent, including where the person is incapacitated. This definition encompasses a range of sexual conduct that could also fall within the definition of sexual harassment. The Title IX Coordinator will determine whether allegations should be treated as sexual harassment or sexual misconduct, based on the specific conduct alleged and the totality of the circumstances. Prohibited forms of sexual misconduct include, but are not limited to: sexual assault, non-consensual sexual contact, sexual exploitation, relationship violence, and stalking.

4.0 Definitions

4.1 Sexual assault is defined as having or attempting to have sexual intercourse with another individual by force or threat of force, without affirmative consent, including where the person is incapacitated. Sexual intercourse includes the penetration, no matter how slight, of the vagina or anus with any body part or object, or oral penetration by a sex organ of another person.

4.2 Non-consensual sexual contact is defined as having sexual contact with another individual by force or threat of force, or without affirmative consent, including where the person is incapacitated. Sexual contact includes intentional contact with the intimate body parts of another (whether directly or through clothing), touching any part of the body of another in a sexual manner, or disrobing or exposure of another. Intimate body parts includes breast, genitals, groin, anus, or buttocks.

4.3 Sexual exploitation occurs when an individual takes non-consensual or abusive sexual advantage of another for their own or another's benefit or advantage.

The following are examples of conduct that could consti-
tute sexual exploitation:

- Unauthorized sharing or posting sexually explicit photos of
another, including a current or former partner.
- Surreptitiously taking pictures or videos of individuals, espe-
cially of private or intimate areas of their body.
- Observing, recording, viewing, distributing or allowing anoth-
er to observe, record, view or distribute, intimate or sexual
images of another individual without that individual's con-
sent.
- Surveillance and other types of observations, whether by
physical proximity or electronic means.

4.4 Affirmative Consent

Affirmative consent is a crucial component of the Caltech
policy/ Affirmative consent is the affirmative, conscious, and
voluntary agreement to engage in sexual activity.

- It is the responsibility of each person involved in the sexual
activity to ensure that they have the affirmative consent of
the other or others to engage in the sexual activity.
- Lack of protest or resistance does not mean consent, nor
does silence mean consent.
- Affirmative consent must be ongoing through a sexual activi-
ty 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.

It is not a valid excuse to alleged lack of affirmative
consent that the respondent believed that the complainant
consented to the sexual activity under either of the following
circumstances:

- The respondent's belief arose from the intoxication or reck-
lessness of the respondent.
- The respondent did not take reasonable steps, in the circum-
stances known to the respondent at the time, to ascertain
whether the complainant affirmatively consented.

It is not a valid excuse that the respondent believed that
the complainant affirmatively consented to the sexual activity
if the respondent knew or reasonably should have known
that the complainant was unable to consent to the sexual
activity under any of the following circumstances:

- The complainant was asleep or unconscious
- The complainant was incapacitated due to the influence of
drugs, alcohol, or medication, so that the complainant could
not understand the fact, nature or extent of the sexual activity
- The complainant was unable to communicate due to a men-
tal or physical condition.

A person who is incapacitated is not capable of giving effective consent to sexual activity. An incapacitated person lacks the physical and mental capacity to make informed, reasonable judgments about whether or not to engage in sexual activity. A person who is incapacitated may not be able to understand where they are, whom they are with, how they got there, or what is happening.

A person may be incapacitated by a temporary or permanent mental or physical condition, sleep, unconsciousness, or be incapacitated as a result of consumption of alcohol or drugs. Incapacitation is a state beyond mere intoxication or "drunkenness." Just because someone is under the influence of alcohol or drugs does not necessarily mean that a person is incapacitated. Impairment must be significant enough to render a person unable to understand the fact, nature, or extent of the sexual activity. In evaluating affirmative consent in cases involving incapacitation, Caltech considers the state of incapacitation of the reporting party and the knowledge of the respondent.

Intoxication, even to the point of incapacitation, does not relieve an individual from responsibility for a policy violation when they engage in sexual conduct without the affirmative consent of the other party or parties.

4.5 Relationship Violence:

Dating Violence means violence committed by a person who is or has been in a social relationship of a romantic or intimate nature with a complainant. The existence of such a relationship shall be determined by the complainant's statement and consideration of the length of the relationship, type of relationship, and the frequency of interaction between persons involved in the relationship.

4.6 Domestic Violence means violence committed by a person

who is a spouse or former spouse, a cohabitant or former cohabitant, a person with whom they have a child, by person similarly situated to a spouse under the law of the state where the violence occurred, and by any other person against an adult or youth victim who is protected from that person's acts under the laws of the state where the violence occurred.

4.7 Stalking is a course of conduct of a sexual or romantic

nature or motivation directed at an individual that would cause a reasonable person to fear for their safety or the safety of others, or suffer substantial emotional distress. Course of conduct means two or more acts, including, but not limited to, acts in which the stalker directly, indirectly, or through third parties, by any action, method, device or means, follows, monitors, observes, surveils, threatens, or

communicates to or about a person or interferes with the person's property. Reasonable person means a reasonable person under similar circumstances and with similar identities to the victim. Stalking that is not sex or gender-based is covered by the Violence Prevention policy and should be reported to Security at campus or the Protective Services Division at JPL and will be handled pursuant to that policy. The following are examples of conduct that depending on the frequency and severity may constitute stalking:

- Repeated unwanted communication, including face-to-face contact, telephone calls, voice messages, emails, text messages, postings on social networking sites, written letters, or gifts;
- Posting picture(s) or information of a sexual nature on social networking sites or other websites;
- Gathering information about the person through the use of public records, online searches, going through the garbage, or contacting the person's family, friends, or co-workers;
- Posting private pictures or videos on school bulletin boards or internet sites;
- Installing spyware on another person's personal devices, including phones or computers;
- Surveillance or other types of observation, including staring or peeping;
- Pursuing, following or showing up uninvited at or near places like classrooms, residence, workplace or other places frequented by an individual;
- Directly or indirectly making threats to the person.

5.0 Retaliation

Retaliation against any member of the Caltech community for making a good-faith report of sexual violence, or for participating in an investigation, proceeding, or hearing conducted by Caltech or a state or federal agency, is strictly prohibited. Overt or covert acts of retaliation, reprisal, interference, discrimination, intimidation, or harassment against an individual or group for exercising their rights under Title IX or other federal and state laws violates this policy and is unlawful. Caltech will take steps to prevent retaliation and will take prompt and appropriate corrective action to stop, and remedy its effects, if retaliation occurs. Individuals who violate this policy may be subject to disciplinary action up to and including termination of employment or permanent separation from Caltech.

6.0 Privacy

Caltech will maintain the privacy of all individuals involved in a report of Prohibited Conduct to the extent possible. All Caltech employees who are involved in the Institute's 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 Prohibited Conduct will only be shared with those individuals who have a "need to know." These individuals will be discreet and will respect the privacy of all individuals involved.

7.0 Preservation of Evidence

Because sexual violence may involve physical trauma and is a crime, individuals who have experienced sexual violence are urged to seek medical treatment as soon as possible. They are strongly encouraged to preserve all physical and digital evidence of the violence. This may be needed to prove criminal sexual violence, or for obtaining a protective order. Individuals who have experienced sexual violence should not shower, bathe, douche, eat, drink, wash their hands, or brush their teeth until after they have had a medical examination. They should save all the clothing
they were wearing at the time of the violence. Each item of clothing should be placed in a separate paper bag, not a plastic bag. They should not clean or disturb anything in the area where the sexual violence occurred. Digital evidence relating to the incident, such as texts, emails, and social media posts, should be also be preserved.

8.0 Resources

Caltech also encourages individuals who have experienced sexual misconduct to seek immediate psychological support and advocacy services provided by Caltech or community services. Campus Security and the Protective Services Division at JPL will contact on-campus and on-lab resources, provide information regarding off-campus resources for support and advocacy, medical treatment, and forensic evidence collection, and will arrange for transportation to access off-campus resources.

24-Hour a Day/7 Days a Week
Campus Security (reporting and/or to
reach confidential or other resources)
(626) 395-5000

Security can assist with safety situations, contact law enforcement, provide transportation vouchers to off-campus resources and contact mental health resources. The caller must simply provide a phone number where the confidential or other resource can reach the caller. Names and other information regarding the incident need not be provided to Campus Security.

JPL Protective Services Division (reporting and/or to
reach confidential or other resources)
(818) 393-3333
(818) 354-3333

The JPL Protective Services Division can assist with safety
situations, contact law enforcement, arrange for transporta-
tion to access off-campus resources, and contact the caller's
choice of a confidential or other resource. The caller must
simply provide a phone number where the confidential or
other resource can reach the caller. Names and other infor-
mation regarding the incident need not be provided to the
Protective Services Division.

8.1 On-Campus Confidential Resources

Caltech offers members of the Caltech community the choice
of seeking confidential counseling. These confidential counsel-
ing services are intended for the personal benefit of the indi-
vidual and offer a setting where various courses of action can
be explored. Except as otherwise provided below, confidential
resources will not share information without the express per-
mission of the individual. Speaking to a confidential resource is
not a report to Caltech, and no investigation will be triggered.

8.1.1 Caltech Mental-Health Professionals

Caltech's mental-health professionals in Student Wellness
Services and the Staff and Faculty Consultation Center will
not report any information about an incident to Caltech,
including to the Title IX Coordinator unless requested by
their client. These professionals are prohibited from breaking
confidentiality unless there is an imminent threat of harm
to self or others or as otherwise permitted by law. When a
report involves suspected abuse of a child under the age of
18, these confidential resources are required by state law to
notify child protective services and/or local law enforcement.
They can be contacted 24 hours a day/7 days a week.

For Students:
(626) 395-8331   Student Wellness Services
                        after hours, press #2 to be connected
                        to on-call service
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:
(800) 367-7474   Empathia/Life Matters–identify yourself
                        as a JPL employee
                        or visit mylifematters.com
                        (Password: JPL)

8.1.2 Caltech Center for Diversity

Designated confidential resources (identified below) in the Caltech Center for Diversity can generally talk to a complainant or respondent without revealing to Caltech any personally-identifying information about an incident. Designation as a confidential resource exempts the resource from reporting information received about Prohibited Conduct to the Title IX Coordinator, but does not exempt them from other legally mandated disclosure obligations, such as under child abuse reporting laws. the CLERY Act and in legal proceedings. For example, when a Clery report is required, a Confidential Resource in the Caltech Center for Diversity will keep the identify of the individual(s) confidential, but will report the nature, date, time and general location of an incident to Security for purposes of Clery reporting. This information will be included in aggregate statistics (with no identifying information) for inclusion in Caltech's Annual Security Report, if required.

- Taso Dimitriadis (626) 395-8108
- Erin-Kate Escobar (626) 395-3221

8.1.3 On-Campus Medical Resources

Note that medical providers (but not psychological counselors) are required to notify law enforcement when they receive a report of assaultive or abusive conduct, including sexual assault.

Caltech's Student Wellness Services is committed to providing compassionate and quality medical help to a student who has experienced sexual violence. Caltech's medical professionals in the Student Health Center will not report any information about an incident to Caltech, including the Title IX Coordinator, unless requested by their client.

Student Health Services
(626) 395-6393
1239 Arden Rd
Pasadena, CA 91106

8.2 Off-Campus Resources

Note that medical providers (but not psychological counselors) at these facilities are required to notify law enforcement when they receive a report of assaultive or abusive conduct, including sexual assault.

Peace Over Violence

(24-hour emergency services offer victims of sexual assault, domestic violence and stalking emotional support, informa-

tion, compassion, accompaniment, referral and advocacy
services.)
892 N. Fair Oaks Avenue, Suite D
Pasadena, CA 91103
(626) 584-6191
(626) 793-3385 (24 hours)

San Gabriel Valley Medical Center (24-hour medical care, emo-
tional support and comprehensive exams including forensic
evidence collection (the "rape kit"). The Sexual Assault
Response Team (SART) Hotline provides immediate connec-
tion to on-call nurse for sexual assault services.").
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 treatment for victims of sexual
assault, including forensic services (the "rape kit")).
(310) 319-4000
(Press "3" to be connected to a clinician)
www.911rape.org

Huntington Memorial Hospital
(24-hour emergency and trauma services. Social workers
available to provide counseling as needed).
100 W. California Blvd.
Pasadena, CA 91105
(626) 421-7733

Planned Parenthood
(Health clinic for emergency contraception and disease
prevention , pregnancy resources, birth control and family
planning).
1045 N. Lake Avenue
Pasadena, CA 91104
(626) 798-0706

9.0 Reporting to Caltech

Anyone who witnesses, experiences, or is otherwise aware of
conduct that the individual believes to be in violation of this poli-
cy, including retaliation, is urged to contact Caltech immediately.
Individuals are encouraged to report to the Title IX Coordinator or a
Deputy Title IX Coordinator.

9.1 Title IX Coordinator and Deputy Coordinators

The Title IX Coordinator is responsible for coordinating Caltech's compliance with Title IX and for Caltech's overall response to conduct falling under Title IX. The Title IX Coordinator oversees all Title IX complaints, monitors outcomes, identifies and addresses any patterns of systemic problems that arise, and assesses effects on the campus climate. The Title IX Coordinator also oversees the implementation and application of Caltech's Title IX related policies within the scope of Title IX and coordinates Caltech's response to all complaints of sexual violence under Title IX to ensure consistent treatment of parties involved, and prompt and equitable resolution of complaints.

The Title IX Coordinator is supported by a Lead Investigator and four Deputy Coordinators, all of whom can answer questions regarding Title IX.

Title IX Coordinator
Hima Vatti, Assistant Vice President for Equity and Equity Investigations
Phone: (626) 395-3132
E-mail: titleix@caltech.edu
Office: 205 Center for Student Services

Lead Investigator
Brian Quillen
Phone: (626) 395-4424
E-mail: bquillen@caltech.edu
Office: 348 Center for Student Services

Deputy Title IX Coordinator for Faculty
Melany Hunt
Phone: (626) 395-4231
E-mail: hunt@caltech.edu
Office: 265 Gates-Thomas

Deputy Title IX Coordinator for Staff and Postdoctoral Scholars
Ofelia Velazquez-Perez
Phone: (626) 395-3819
E-mail: Ofelia.Velazquez-Perez@caltech.edu
Office: 206 Central Engineering Services

Deputy Title IX Coordinator for Students
Allie McIntosh
Phone: (626) 395-1743
E-mail: allie@caltech.edu
Office: 105 Center for Student Services

Deputy Title IX Coordinator for JPL
    Jackie Clennan-Price
    Phone: (818) 393-0016
    E-mail: Jackie.A.Clennanprice@jpl.nasa.gov
    Office: Human Resources T1720-149

9.2 Responsible Employees

If an individual discloses Prohibited Conduct to any Responsible Employee, the responsible employee must report to the Title IX Coordinator all relevant details about the alleged conduct.

At campus, the following are Responsible Employees:
- Title IX Deputies
- Staff members with a supervisory or managerial role, who do not have legally protected confidentiality
- Security Officers
- Residential Life Coordinators
- Resident Associates
- Coaches
- Employee Relations consultants
- Faculty members who supervise a research laboratory or group, or who have administrative responsibilities.

At JPL, the following are Responsible Employees:
- Title IX Deputy for JPL
- Supervisors and managers
- Employee Relations Representatives
- Human Resources Business Partners
- Education Office staff

Caltech is committed to protecting the privacy of all individuals involved in a report of Prohibited Conduct. All employees involved in the response to a report of Prohibited Conduct 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.

If a member of the Caltech community would like support and guidance in filing a complaint, they may 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. They may also contact of the EEO Coordinators identified in the Nondiscrimination and Equal Employment Opportunity Policy.

9.3 Anonymous Reporting

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

Contacting one of these anonymous reporting resources may
trigger an investigation, and if the reporting party shares
personally identifying information, they will be notified if an
investigation occurs.

9.4 Notification of Law Enforcement

Individuals who have experienced sexual violence are encouraged
to notify local law enforcement. Caltech will provide assistance
in notifying law enforcement if the individual so chooses. An indi-
vidual who has experienced sexual violence also has the right to
decline to notify law enforcement or Caltech.

   Caltech has an obligation under California law to report incidents
of sexual violence to law enforcement; however, Caltech will not
report identifying information about the complainant without the
complainant's consent after being notified of their right to have
personally identifying information withheld. If the complainant does
not consent to be identified, personally identifying information
about the respondent also will not be provided.

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

10.0 Requests for Confidentiality or that Complaint Not Be Pursued

In matters falling under Title IX, if a member of the Caltech communi-
ty discloses an incident to the Title IX Coordinator, a Deputy Title IX
Coordinator or a Responsible Employee, but requests that their name
not be used, that the Institute not pursue an investigation, 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 weigh the request for
confidentiality against factors including, but not limited to, the seri-
ousness of the conduct, circumstances that suggest there is a sig-
nificant risk that the accused will commit further acts of Prohibited
Conduct, whether there was a weapon involved, and the age of a
student victim.

   The Title IX Coordinator or designee will determine the appropri-
ate manner of resolution.

   The Title IX Coordinator or designee will attempt to address the

conduct consistent with the complainant's request not to use their name or their request not to pursue an investigation or that no disciplinary action be taken, while also protecting the health and safety of the complainant and the Institute community.

Caltech's ability to fully investigate and respond may be limited if the complainant requests anonymity or declines to participate in an investigation. Caltech will, however, take other action to limit the effects of the Prohibited Conduct and prevent its recurrence.

In those instances where the Title IX Coordinator or designee determines that Caltech must proceed with an investigation despite the request of the complainant, the Title IX Coordinator or designee will inform the complainant of Caltech's intention to initiate an investigation. The complainant is not required to participate in the investigation.

In all cases, the final decision on whether, how, and to what extent Caltech will conduct an investigation, and whether other measures will be taken in connection with the report of Prohibited Conduct, rests solely with the Title IX Coordinator or their designee.

11.0   Reports Involving Minors

Every member of the Caltech community, who knows of, or reasonably suspects, child abuse, including any Prohibited Conduct involving a minor, has a personal responsibility to report to Caltech Security or the JPL Protective Services Division immediately. A minor under the age of sixteen is not considered to be capable of giving valid affirmative consent to sexual activity under this policy. Caltech employees who are mandated reporters have additional reporting obligations, including reporting immediately to LA County Child Protection and/or the local police department. See the Violence Prevention policy for more information.

12.0   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.

13.0   Emergency Notifications and Timely Warnings

In the event of a dangerous situation on campus that involved an immediate threat to the health or safety of students or employees, Caltech will issue an Emergency Notification consistent with its Emergency Notification procedures. In the event Caltech believes that there is a serious or continuing threat to the campus community, Caltech will issue a Timely Warning consistent with its Timely

Warning procedures. Emergency Notifications and Timely Warnings do not disclose the name of the victim.

14.0 Clery Reporting

The Clery Act requires Caltech to issue an Annual Security and Fire Safety Report, which includes crime statistics for sexual assault (rape, fondling, incest and statutory rape), domestic violence, dating violence and stalking. Campus Security gathers these crime statistics from security reports, Pasadena Police Department information, JPL and reports by Campus Security Authorities. Crime statistics do not disclose any identifying information about a complainant, respondent, witnesses or others. For more information and statistics for the past three years, see the current Annual Security and Fire Safety Report.

15.0 Contacting Government Agencies

Employees, students and others participating in Caltech's educational programs or 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 may file complaints with the California Department of Fair Employment and Housing (DFEH) at https://www.dfeh.ca.gov/contact-us or the United States Equal Employment Opportunity Commission (EEOC) at https://www.eeoc.gov. Complaints can also be directed to the Bureau for Private Postsecondary Education at http://bppe.ca.gov.

   NASA funded program participants may file a complaint at AssistedProgramComplaint@nasa.gov or find more information at https://missionstem.nasa.gov/filing-a-complaint.html. NSF funded program participants may file a complaint with the Office of Diversity and Inclusion at programcomplaints@nsf.gov, (703) 292-8020 or find more information at https://www.nsf.gov/od/odi/harassment.jsp. Filing a complaint with a federal agency under Title IX must be done within 180 days after an alleged discriminatory or harassing event and there is no requirement to exhaust remedies through Caltech's internal procedures before filing directly with a federal agency. Participants in programs funded by other federal agencies providing federal financial assistance to Caltech may file directly with those agencies.

16.0 Informational Resources

Information on Prohibited Conduct, as well as copies of Caltech's Gender-Based Misconduct, Nondiscrimination and Equal Employment Opportunity, Unlawful Harassment, and Violence Prevention Policies are available from Caltech's Title IX Coordinator and Deputy Coordinators, Caltech's EEO Coordinators, Human Resources, Student Affairs and Deans offices, the Caltech Center for Diversity, Resident Associates, the Staff and Faculty

Consultation Center, and Employee & Organizational Development at campus, and the Deputy Title IX Coordinator, EEO Coordinator, and Human Resources Business Partners at JPL. The Policies are published in the Caltech Catalog and on the following Caltech and JPL websites: Caltech Human Resources, JPL Human Resources, Title IX, and Student Affairs.

Related Policies and Procedures:
- Procedures for Responding to and Resolving Complaints of Gender-Based Misconduct
- Nondiscrimination and Equal Employment Opportunity
- Unlawful Harassment
- Procedures Regarding Unlawful Harassment
- Violence Prevention

PROCEDURES FOR RESPONDING TO AND RESOLVING COMPLAINTS OF GENDER-BASED MISCONDUCT

Caltech will take prompt and appropriate action to address all reports of Prohibited Conduct in a fair and impartial manner. The complainant, respondent, and all other participants in the process will be treated with dignity, care and respect.

Caltech's policy reflects its commitment to support and encourage individuals who have been subjected to Prohibited Conduct to come forward. Caltech takes all allegations of Prohibited Conduct seriously and responds appropriately. Caltech's policy is also intended to ensure that individuals accused of engaging in Prohibited Conduct are not prejudged; that they have notice and a full and fair opportunity to respond to allegations before findings and conclusions are reached; and that decisions are based on the evidence gathered in a process that is fair to both complainants and respondents. Caltech will conduct a fair, impartial, timely and thorough investigation that provides all parties with appropriate due process.

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 Prohibited Conduct 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 protection and well-being of the complainant and the campus community.

Reporting to Caltech

A member of the Caltech community who wishes to report Prohibited Conduct should do so as soon as possible after the incident, 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 the Title IX Coordinator (hereinafter "Title IX Coordinator or designee"), Lead Investigator, or a Deputy Title IX Coordinator, or other responsible employee listed in the policy, who will then notify the Title IX Coordinator in cases falling under Title IX.

Title IX Coordinator
Hima Vatti
Phone: (626) 395-3132
E-mail: titleix@caltech.edu
Office: 205 Center for Student Services
Initial Title IX Assessment

For reports of Prohibited Conduct covered by Title IX, Caltech's Title IX Coordinator or designee 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 in the policy.

The complainant will be provided with information on the complainant's rights and options under the Institute's Gender-Based Misconduct policy (hereinafter the 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. Appropriate interim measures will be instituted and may be modified. The imposition of interim measures is not indicative of a determination of responsibility or any other outcome.

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, the individual will be provided with information on the respondent's rights and options under the 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, whether there is a potential violation of the policy, and if there is a potential policy violation an appropriate approach to resolution can be determined. Thereafter, the Title IX Coordinator may refer the complaint for the appropriate disposition, depending on a variety of factors, such as the complainant's request that their 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 Prohibited Conduct 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 unless there is a serious or continuing threat to the Caltech community. In implementing the approach, the Title IX Coordinator will inform and coordinate with the appropriate responsible administrator(s): Provost, Assistant Vice President for Human Resources, Deans, Associate Deans, Associate Vice President for Human Resources on campus, or Director for Human Resources at JPL.

Caltech will investigate reports of Prohibited Conduct consistent with its obligations under applicable law. The Title IX Coordinator will seek consent from the complainant to proceed with action. If the complainant does not consent, Caltech will still take all reasonable steps to protect the complainant, including instituting appropriate interim measures. If the Complainant refuses to have their 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 their right to file a criminal complaint or to choose not to notify law enforcement. If a complainant requests that the complaint not be pursued, the request will be considered consistent with the provisions of Section 9.0 of the policy.

In cases of alleged Prohibited Conduct at JPL not falling under Title IX, the above described initial assessment will be done by the JPL Deputy Title IX Coordinator or their designee.

Interim Measures

Interim measures are actions taken by Caltech in response to a report of Prohibited Conduct. Upon receipt of a report, Caltech will take prompt measures to protect the rights of the parties as appropriate. Caltech will immediately assess whether there is a threat to the complainant, the respondent and/or other members of the community and will take steps necessary to address such risks. These steps may include interim safety measures, which may be made at any time, to provide for the safety of individuals and the campus community.

Appropriate administrative changes and/or academic changes may be made, if requested and reasonably available, at any stage in the process to protect the rights of either party. They will be made by the Title IX Coordinator in coordination with responsible administrators. For students, these changes might include changes to housing arrangements, counseling services, academic accommodations, "no contact" orders between individuals, restrictions on access to Caltech or to specific Caltech areas or activities, persona

non grata status, escorts, limitations on extracurricular or house activities, 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.

Changes affecting faculty, postdoctoral scholars and staff, including 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.

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.

The imposition of interim measures is not indicative of a determination of responsibility or any other outcome. These measures may be modified at any time and may be kept in place after a final investigative decision is reached.

All parties are expected to comply with any interim measures that may be imposed. Failure to comply with interim measures may be grounds for disciplinary action. A party may be found in violation of the policy for failure to comply with an interim measure even if they are found not responsible for the underlying report of Prohibited Conduct.

Informal Options

Individuals who believe they have been subjected to Prohibited Conduct may choose to resolve their 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 them to stop. This is a personal step taken solely among the relevant parties.
- Speaking to members of the Student Wellness Services, 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 with the Title IX

- Coordinator and complainant 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 Options

A complainant alleging Prohibited Conduct may elect to pursue a formal option. Formal options include:

Administrative Resolution

In cases alleging Prohibited Conduct covered by Title IX, the Title IX Coordinator or designee, with the complainant's and the respondent's agreement, may offer the opportunity to resolve the complaint by Administrative Resolution. Administrative Resolution provides an opportunity for the respondent to accept responsibility for their alleged conduct and proceed to a resolution without a formal investigation. Complainants and respondents participating in this process may have an advisor of their choice accompany them when reporting, or responding to, allegations of Prohibited Conduct. The advisor may not speak on behalf of the individual they are accompanying.

If the Administrative Resolution option is agreed to by a 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 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 conduct, the respondent will sign a written acknowledgement and the matter will be referred to the appropriate decision maker (hereinafter "decision maker or designee") 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 only appeal the sanction imposed.

In cases of alleged Prohibited Conduct at JPL not falling under

Title IX, the above described Administrative Resolution process will be administered by the JPL Equal Employment Opportunity Officer or their designee.

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.

Remedy-Based Resolution

In appropriate cases at any time during the process, the Title IX Coordinator or the decision maker may propose a Remedy-Based Resolution (RBR) as a means of resolving a complaint of Prohibited Conduct. The intent of a RBR is to address the underlying issues that contributed to the subject incident by imposing non-disciplinary remedies focused on education around issues of concern, remediation of problematic and unhealthy behaviors and the use of other strategies to remedy the situation. Both parties must voluntarily agree to all the terms of the RBR as the complete and final resolution of the Title IX complaint(s).

Mediation

In appropriate cases as determined by the Title IX Coordinator, mediation may be offered to the parties. Mediation is a process whereby a facilitator (mediator) works with the complainant and respondent to attempt to reach a mutually agreeable resolution of a complaint of Prohibited Conduct. Both parties must voluntarily agree to all the terms of a mediated resolution as the complete and final resolution of the Title IX complaint(s).

Formal Complaint Process

Caltech takes all allegations of Prohibited Conduct seriously and responds appropriately. The following procedures apply to formal investigations of complaints of Prohibited Conduct.

For complaints involving students, staff or faculty, the Title IX Coordinator will refer the investigation to the Lead Investigator and appropriate Deputy Title IX Coordinator. For complaints involving responding parties outside the Institute, the Title IX Coordinator will oversee the response. Caltech's investigation will occur independently from any legal/criminal proceedings that may take place. Caltech may defer fact gathering for an appropriate time during a criminal investigation.

Investigators will be trained regularly on issues related to Prohibited Conduct and investigation processes that protect the safety of all involved and promotes accountability. The investigators must be impartial and free of any conflict of interest.

All participants in an investigation will receive a fair and impartial process and be treated with dignity, care, and respect. The pur-

pose of the investigation is to determine the facts relating to the complaint and decisions are based on the evidence. Evidence may include parties and witness testimony and any documents relating to the complaint. Caltech's policy and procedures are intended to ensure that individuals reported for Prohibited Conduct are not prejudged and are provided with adequate notice and an opportunity to be heard regarding the allegations made against them. Consistent with federal and state law, 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 sexual, romantic, or intimate relationship between the complainant and respondent itself does not by itself imply consent or preclude a finding of Prohibited Conduct.

The investigation will be treated as private to the extent possible. 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. Investigatory meetings will not be recorded by any participant involved in a case. Investigation files will be maintained by the Title IX Office.

Caltech does not tolerate retaliation and will take steps to prevent retaliation and strong responsive action if it occurs. All participants, including the complainant and respondent, are protected against retaliation and will be advised to notify Caltech immediately if retaliation occurs.

Investigation Process

- The formal investigation process begins when the complainant files a formal complaint. Within a reasonable length of time after the complaint has been filed, the Title IX Coordinator will notify both parties when the Title IX Office is starting an investigation. That notification will summarize the allegations and underlying reported behavior, as well as identify the assigned investigator(s). The complainant and respondent also will be provided with a copy of the Gender-Based Misconduct policy and accompanying procedures.

- Either party may object to an investigator(s) if they believe that investigator has a conflict or cannot be impartial. The Title IX Coordinator will consider any objections and notify the parties of the decision related to the investigator(s).

- After a reasonable amount of time to review the notice of investigation and applicable policies, the parties will be given equal opportunity to meet with the investigator(s). In those meetings, the investigator(s) will gather evidence about the allegations, including any documents or written statements submitted by either party.

- The complainant and respondent may have an advisor of their

choice accompany them in the investigatory process or other meetings with the party related to the complainant. The advisor may not speak on behalf of the individual they are accompanying.

- Throughout the process, the parties may suggest witnesses and documents to the investigator(s), as well as questions for the investigator(s) to ask the other party and any witnesses. The investigator(s) will determine whether the suggestions are relevant and appropriate. Caltech asks the parties to keep the investigation private, but cannot prohibit the parties from discussing the investigation with others in connection with identifying evidence for the investigator(s) to gather.

- The investigator(s) will interview relevant witnesses and gather other evidence related to the allegations. Witnesses may also submit documents or written statements to the investigator(s).

- In complaints covered by Title IX, the investigators will investigate any allegations that alcohol or drugs were involved in the incident.

- The complainant and respondent will be given equal opportunity to review and respond to all the evidence gathered by the investigator(s).

- The investigator(s) will prepare a draft report which includes their recommended findings of fact and related analysis regarding the allegations. The complainant and respondent will have the opportunity to review and respond to the draft report. If any information is presented by either party that impacts the investigators' analysis or findings it will be shared with the other party and they will be given an opportunity to respond.

- Once the report is finalized, it will be provided to the complainant, respondent, and decision maker.

- For cases in which a respondent faces severe disciplinary sanctions (e.g. involuntary temporary or permanent separation from the Institute) and the credibility of the parties or witnesses is central to the adjudication of the allegations, the decision maker and the lead investigator will meet with the parties, and others with whom the decision maker deems appropriate prior to making a decision regarding the case. The parties may suggest questions to ask the other party and any witnesses with whom the decision maker is meeting. The lead investigator will facilitate the questioning and will have the discretion to exclude any question(s) that they determine is inflammatory or otherwise inappropriate. To facilitate access while maintaining the physical separation of the parties, the party submitting the questions will have access to the live exchange(s) via telephone conference or other appropriate technology, and may submit follow-up questions via email or other appropriate technology during this process.

- The decision maker will make a decision regarding the allegations based on the report, the parties' responses to the report, the information gathered in the decision maker's meetings with the parties and others, and the decision maker's assessment of credibility in cases where the credibility of any party or witness is relevant. When credibility is at issue, the decision maker will not rely on statements made by a party or witness if that person declines to meet with the decision maker.

- The decision maker, consulting with the Title IX Coordinator as appropriate, will determine the appropriate sanction or remedy.

- The complainant and respondent will be notified in writing with a closing investigation letter of the outcome of the process, including any sanctions or remedies. This notice will also include the option to appeal.

- 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). This time frame may be extended depending on factors, including but not limited to, the complexity of the case. Both parties will be kept informed of the status of the investigation.

- The Title IX Coordinator will be informed of the outcome of the investigation and any appeal in order to carry out their responsibilities to consult on sanctions, monitor outcomes, identify and address any patterns, and assess effects on the campus climate.

- Exceptions to or modification of these procedures can be made by the Title IX Coordinator or designee, Provost, Dean or Associate Deans, Associate Vice President for Human Resources, or Director for Human Resources at JPL.

Student Policy Violations: Complainants and Witnesses

A student who participates as a complainant or witness in an investigation of sexual assault, dating violence, domestic violence or stalking generally will not be subject to disciplinary sanctions for a violation of Caltech's student conduct policies, including but not limited to the 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 or involves plagiarism, cheating, research misconduct or other forms of academic dishonesty.

Standard of Evidence

The investigator(s) and the decision maker will use the preponderance of evidence standard in determining whether Prohibited Conduct occurred. A preponderance of the evidence means that it is more

likely than not that the incident occurred. When the investigator(s)/decision maker is presented with two different but plausible versions of the incident, credibility determinations may affect the outcome.

Recommended Findings

The investigator(s) will report their recommended findings of fact regarding the charges to the appropriate decision maker. The decision maker shall be determined based upon the respondent's affiliation (the Provost for faculty, the relevant Dean for students, the Assistant Vice President for Human Resources for postdoctoral scholars and campus staff, or the Deputy Director for Human Resources at JPL for JPL employees) or their designees.

Resolution

Once the decision maker has received the report and conducted the meetings with the parties and others they deem necessary to making a decision, the decision maker will reach conclusions regarding the allegations and if warranted will impose any sanctions they deem to be appropriate.

The conclusions that might be reached may include, but are not limited to, the following possibilities:

1. A violation of Caltech policy occurred.
2. Inappropriate behavior occurred, but did not constitute a violation of Caltech policy.
3. The complaint was not supported by the evidence.
4. The complaint was brought without any basis or without a reasonable, good faith belief that a basis existed.

The decision maker shall consult with the Title IX Coordinator and any other administrators that they deem appropriate in determining any sanctions for policy violations. The complainant and respondent simultaneously will be informed in writing of the results of the process and the parties' right to appeal and the procedures for appeal.

If a violation of Caltech policy has occurred, appropriate sanctions will be imposed. The decision maker may impose any one or more of the sanctions listed below:

• Verbal warning
• Training
• Mandatory counseling/coaching
• A formal written warning placed in the respondent's file
• Exclusion from participation in certain activities for specified period of time

- Banned from campus
- Suspension of the right to accept new graduate students or postdoctoral scholars
- Transfer of advisees
- Removal from positions of administrative responsibility
- Removal from housing
- Removal from a supervisory position
- Involuntary leave of absence/suspension
- Expulsion
- Termination of employment
- Permanent separation from the Institute
- Revocation of admission
- Other sanctions instead of, or in addition to, those specified above
- Multiple sanctions may be imposed

If the respondent was found not to have violated Caltech's policy, but the investigation concluded that the individual committed some other wrongful or improper act, appropriate 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 Prohibited Conduct, and to correct any discriminatory effects on the complainant and others, as appropriate.

Results of disciplinary proceedings may be disclosed consistent with applicable law, including FERPA, Title IX, and the Clery Act. Upon request, Caltech will disclose the results of a disciplinary proceeding against a student who is the alleged perpetrator of any crime of sexual violence to the alleged victim.

Appeals

Appeals must be in writing and submitted within ten (10) calendar days of notification of the decision to the appropriate administrator identified below. Appeals of decisions resulting from the Formal Complaint process are limited to one or more of the following grounds: a procedural error or due process violation occurred which would have significantly affected the outcome of the complaint; there is new evidence (including a new witness) that was not available during the process which would have significantly affected the conclusions of the decision maker; or the sanction is substantially disproportionate to the findings. Appeals of decisions resulting from the Administrative Resolution process can be made only on the ground that the sanction is substantially disproportionate to the acknowledged conduct.

If a party submits an appeal, the other party will have the oppor-

tunity to submit a written response to the appeal within ten (10) calendar days of the filing of the appeal. The complainant and the respondent simultaneously will be informed, in writing, of the outcome of the appeal. Appeal decisions are final.

Decisions of the Provost may be appealed to the Office of the Provost or designee. Decisions of the Dean of Undergraduate Students or Dean of Graduate Studies may be appealed to the Vice President for Student Affairs or designee. Decisions of the Assistant Vice President for Human Resources may be appealed to the Associate Vice President of Human Resources or designee. Decisions of the Deputy Director for Human Resources at JPL may be appealed to the Director for Human Resources at JPL or designee.

Further Complaints

If the corrective action does not end the Prohibited Conduct, the complainant should immediately notify the Title IX Coordinator, Lead Investigator, or a Deputy Title IX Coordinator, the Provost or a Division Chair, Dean or Associate Dean, EOD Director; or at JPL, the Section Manager, Talent Management. In such cases, the complainant has the right to file another complaint.

- 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 their own safety, or who is interfering with the use of a public way, is guilty of disorderly conduct, which is a misdemeanor.
- It is unlawful for a person to possess nitrous oxide (e.g.whippets) with the intent to inhale for purposes of altering their mood or mental functioning.

NONDISCRIMINATION AND EQUAL EMPLOYMENT OPPORTUNITY

Caltech is committed to equal opportunity for all persons regardless of 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, gender expression, sexual orientation, protected military or 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. Discrimination is unfair or unequal treatment based on protected characteristic and/or applying policies and practices that have an unfavorable impact

on individuals based on protected characteristics. Harassment on the basis of any legally protected characteristic is a form of discrimination and is likewise prohibited by this policy. The law prohibits discrimination by co-workers and third parties as well as supervisors and managers. Interns, volunteers and persons performing services under a contract with Caltech are also covered by this policy. Caltech will take all reasonable steps to eliminate discrimination, and harassment in its work and academic environment. Complaints concerning sexual and gender-based discrimination and harassment and sexual misconduct are governed by the Gender-Based Misconduct Policy.

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 following individuals have been designated as Equal Employment Opportunity Coordinators: the Provost is the coordinator for faculty, the Assistant Vice President for Equity and Equity Investigations is the coordinator for campus staff and volunteers, the Associate Deans of Students are the coordinators for undergraduate students and interns, the Dean of Graduate Studies is the coordinator for graduate students and interns, and the Director for Human Resources at the Jet Propulsion Laboratory is the coordinator for employees, interns and volunteers assigned there. The Assistant Vice President for Equity and Equity Investigations has been designated as Caltech's Title IX Coordinator. The contact number is (626) 395-3132, email: TitleIXCoordinator@caltech.edu, or the office in Room 205, Center for Student Services. The Title IX Coordinator is supported by three deputy coordinators. https://titleix.caltech.edu/

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.

Individuals who witness or experience conduct they believe to be in violation of this policy are urged to contact any of the above-mentioned coordinators, the individuals identified in Caltech's harassment policy, the Caltech Office of Equity and Title IX or JPL Employee Relations Group immediately. In addition, they may utilize Caltech's anonymous hotline at 626-395-8787. Complaints will be investigated promptly. Confidentiality will be maintained to the extent possible. Supervisors and managers are required to report any complaints of discriminatory conduct to one of the above-designated coordinators so that Caltech can try to resolve the complaint internally. Individuals who violate this policy may be subject to disciplinary action up to and including termination of employment or permanent separation from Caltech.

In addition, employees who believe they have been subject to harassment or discrimination 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. 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). Complaints may also be directed to the Bureau for Private Postsecondary Education at http://bppe.ca.gov.

Caltech will conduct a fair, timely, and thorough investigation into complaints within the scope of this Policy to determine what occurred and take reasonable steps to remedy the effects of any discrimination and prevent recurrence of the behavior. Caltech provides all parties with appropriate due process and reaches reasonable conclusions based on the evidence collected. Caltech takes appropriate action, including disciplinary measures, when warranted.

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 Caltech's

equal opportunity and affirmative action policies.

Related Policies and Procedures:
- Unlawful Harassment
- Procedures Regarding Unlawful Harassment
- Gender-Based Misconduct
- Procedures for Responding to and Resolving Complaints of Gender-Based Misconduct
- Disability and Reasonable Accommodation

SUBSTANCE ABUSE

1.0 Policy

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 the Drug-Free Workplace Act of 1988 and the Drug-Free Schools and Communities Act Amendments of 1989, 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.

2.0 Scope

2.1 Prohibited Conduct

The unlawful use, manufacture, distribution, cultivation, dispensation, possession, sale, or purchase of or offer to sell or purchase 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. Despite recent changes to California law, marijuana still is a controlled substance under federal law, and therefore, the use, manufacture, distribution, cultivation, dispensation, possession, sale, purchase of or offer to sell or purchase marijuana on the Caltech campus or its offsite locations, including JPL, or as any part of its activities, continues to be prohibited. The recreational use of nitrous oxide is also prohibited under this policy.

In addition, every employee is prohibited from being under the influence of controlled substances, alcohol, or any substance that may impair the employee's ability to perform their job duties safely or productively, or that may otherwise impair their senses, coordination, or judgment while on duty. Any employee reporting to work (or otherwise at work) under the influence of, or having present in their 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 their supervisor. Caltech may require an employee to submit to drug and alcohol testing consistent with Institute policy and applicable federal and state law. Testing procedures that apply to JPL employees are available on the JPL Human Resources website.

2.2 Requirements for Employees and Students

As a condition of continued enrollment, every student is required to comply with this policy. As a condition of employment, all Caltech employees (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 involuntary leave or expulsion from Caltech may be invoked for violation of this policy and that intoxication is never an excuse for misconduct. Caltech may contact a student's parents when a student under 21 violates this policy. If a student's behavior with respect to alcohol and drugs presents a danger to themselves or others, Caltech may inform the parents.

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.

A faculty, staff, postdoctoral scholar or student who is convicted (including a plea of nolo contendere [no contest]) of a criminal drug statute violation occurring in the workplace or on Caltech property must notify Caltech in writing within five (5) calendar days after the conviction.

2.3 Third Party Requirements

Campus employees should inform the Executive Director of Human Resources and students should inform their dean. JPL employees should inform the Manager of Employee Relations.

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.

3.0 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 they are losing control over the use of the substance and that they need 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 and the fetus. When two or more substances are combined, the effect is often stronger than their additive sum.

4.0 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 $10,000,000.

4.1 Examples
- 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 their own safety, or who is interfering with the use of a public way, is guilty of disorderly conduct, which is a misdemeanor.
- It is illegal for a person to possess nitrous oxide (e.g. whippets) with the intent to inhale it for purpose of altering their mood or mental functioning.

5.0 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 (800) 367-7474. Students are encouraged to seek assistance from the Student Wellness Services (SWS) 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 SWS 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, SWS, 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.

6.0 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; faculty, staff, postdoctoral scholar and student assistance programs; and
3. disciplinary action that may be imposed on faculty, staff, post-doctoral 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.

7.0 Supervisor's Responsibilities

If an employee is suspected of violating this policy, the employee's supervisor should consult with the Director of Employee and Organizational Development (EOD) at campus or the Employee Relations Department of the Human Resources Directorate at JPL regarding appropriate actions, which may include an investigation, and discipline up to and including termination of employment. 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 Employee Relations Department of the Human Resources Directorate at JPL, to assess and address the situation and to remove the employee from the worksite if necessary.

8.0 Caltech Sanctions

Caltech will impose sanctions for violations of or failure to comply with the requirements of this policy. These sanctions will be consistently enforced and penalties will depend on the severity of the offenses. Penalties may include employment termination and student expulsion from Caltech, and referral to law enforcement for the most serious violations of the law and this policy (e.g. the manufacture or distribution of banned substances). 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

1.0 Policy

It is the policy of Caltech to provide a work and academic environment free of unlawful harassment ("harassment"). Harassment is

a form of misconduct that includes unwelcome physical, verbal or non-verbal conduct which results in a person feeling intimidated, threatened, humiliated or demeaned, and is likely to interfere with an individual's work or education, or adversely affects 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 gender identity, sexual orientation, military or veteran status, or any other characteristic protected by state or federal laws ("protected characteristics"), is unlawful and is strictly prohibited, as are all forms of sexual intimidation, exploitation, and violence. Caltech is committed to educating the community in ways to prevent its occurrence. Complaints concerning sexual and gender-based discrimination and harassment and sexual misconduct are governed by the Gender-Based Misconduct Policy.

Conduct becomes unlawful harassment when 1) enduring the offensive conduct becomes a condition of continued employment, or 2) the conduct is enough to create a work or academic environment that a reasonable person would consider intimidating, hostile, or abusive. Anti-discrimination laws also prohibit harassment against individuals in retaliation for filing a discrimination claim, testifying, or participating in any way in an investigation, proceeding, or lawsuit under these laws; or opposing employment practices that they reasonably believe discriminate against individuals, in violation of these laws. Petty slights and annoyances will not rise to the level of illegality.

Offensive conduct may include, but is not limited to, offensive jokes, slurs, epithets or name calling, physical assaults or threats, intimidation, ridicule or mockery, insults or put-downs, offensive objects or pictures, and interference with work or academic performance.

Caltech, as appropriate, will conduct a fair, timely, and thorough investigation into complaints within the scope of this policy to determine what occurred and take reasonable steps to remedy the effects of any harassment and prevent recurrence of the behavior. Caltech provides all parties with appropriate due process and reaches reasonable conclusions based on the evidence collected. Caltech 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, and the prevention of abusive conduct, consistent with federal and state legal requirements.

Behavior evidently intended to dishonor protected characteristics such as race, 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. Some kinds of

behavior that are clearly intended to harass, while inappropriate and not tolerated at Caltech, may not be unlawful. These types of behavior may be dealt with for students through the student disciplinary process and for employees through supervisory intervention, including the 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. Every complaint is considered based on the totality of the circumstances. A single incident, if unusually severe, may constitute harassment.

The following are examples of behaviors that may constitute harassment:

- An adviser tells a student not to take a certain course because the adviser says that other minority students have had difficulty in the course.
- A disabled individual is not included in an off-site outing because of lack of mobility.
- A supervisor assigns only menial tasks to a minority staff member whose job and qualifications merit more complex work.
- A student tells racially offensive jokes within a study group session with other students.
- An individual is ostracized from group activities because of their national origin.
- Making or using derogatory comments, epithets, slurs or jokes based on age.

2.0 Scope

This policy applies to all members of the Caltech community (students, faculty, supervisory and nonsupervisory staff, postdoctoral scholars, volunteers, interns, vendors, independent contractors, persons performing services under contract with Caltech, visitors and any other individuals regularly or temporarily employed, studying, living, visiting, or otherwise participating in Caltech's employment and education programs and activities). This policy applies to conduct occurring on Institute controlled property, at Institute sponsored events and in Institute employment and education programs and activities regardless of location.

Members of the Caltech community are encouraged to report unlawful harassment regardless of where the incident occurred or who committed it (i.e., a stranger or non-stranger). Even if Caltech does not have jurisdiction over the person accused of harassment, Caltech will still take prompt action and reasonable steps to remedy the effects of the harassment and prevent any reoccurrence of the behavior.

3.0 Prohibition against Retaliation

No member of the Caltech community will be retaliated against for

making a good-faith report of harassment or for participating in an investigation or proceeding 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 federal and state laws is unlawful. 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 of employment or permanent separation from Caltech.

4.0 Privacy

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

5.0 Confidentiality

Confidentiality generally 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 in Section 6.0. They are prohibited from breaking confidentiality unless there is an imminent threat of harm to self or others or as otherwise permitted by law. 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.

6.0 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. 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. Talking to any of these staff members does not constitute reporting an incident to Caltech.

An individual who has experienced unlawful harassment and who first requests confidentiality, may later decide to file a complaint with Caltech. The mental-health professionals and other confidential resources listed below will provide the individual with assistance in filing a complaint if the individual wishes to do so.

Mental-health professionals in the Student Counseling Center and the Staff and Faculty Consultation Center provide men-

tal-health counseling services to the campus community. The JPL Employee Assistance Program provides mental-health counseling services to the JPL community. They will not report any information about an incident to Caltech, including the Title IX Coordinator unless requested by their client. 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:
    (800) 367-7474   Empathia identify yourself as a JPL
                               employee
    http://www.mylifematters.com/ (Password: JPL)

Other Confidential resources are:

Caltech Center for Diversity (students):
    (626) 395-3221 or (626) 395-8108

Campus Hotline:
    (626) 395-8787 or (888) 395-8787
JPL Ethics Hotline:
    (818) 354-9999

7.0 Equal Employment Opportunity Coordinators and Title IX Coordinator

The following individuals have been designated as Equal Employment Opportunity Coordinators (EEO Coordinators): the Provost is the coordinator for faculty, the Assistant Vice President for Equity and Equity Investigations is the coordinator for campus staff and volunteers, the Associate Deans of Students are the coordinators for undergraduate students and interns, the Dean of Graduate Studies is the coordinator for graduate students and interns, and the Director for Human Resources at the Jet Propulsion Laboratory is the coordinator for employees, interns and volunteers assigned there. The Assistant Vice President for Equity and Equity Investigations has been designated as Caltech's Title IX Coordinator. The contact number is (626) 395-3132, email: TitleIXCoordinator@caltech.edu, or visit the office in Room 205, Center for Student Services.

8.0 Reporting to Caltech

Anyone who witnesses, experiences, or is otherwise aware of conduct that they believe to be in violation of this policy, including retaliation, is urged to contact Caltech immediately. To report a claim or request any assistance and guidance contact the Equity and Title IX Office at campus or the JPL Employee Relations Group.

Any person in a supervisory role must report any complaints of unlawful harassment of which they become aware to one of the designated EEO Coordinators listed in Section 7.0.

If a member of the Caltech community would like support and guidance in filing a complaint, they may contact one of the Deans or Associate Deans, the Assistant Vice President for Equity and Equity Investigations in Human Resources, JPL's Manager of Employee Relations, or the JPL Section Manager of Talent Management or Human Resources Business Partners at JPL. They may also contact the EEO Coordinators.

9.0 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 the reporting party shares personally identifying information, they will be notified if an investigation occurs.

10.0 Contacting the Outside Agencies

In addition, employees who believe they have been unlawfully harassed 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. 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. Complaints may also be directed to the Bureau for Private Postsecondary Education at http://bppe.ca.gov.

11.0 Informational Resources

Information on unlawful harassment, as well as copies of Caltech's Nondiscrimination and Equal Employment Opportunity, Unlawful Harassment, and Sexual Misconduct, and Violence Prevention policies are available from Caltech's Title IX Coordinator and Deputy Coordinators, Human Resources, Student Affairs and Deans offices, the Caltech Center for Diversity, Resident Associates, the Staff and Faculty Consultation Center, and Employee & Organizational Development at campus, and Employee Relations and the Human Resources Business Partners 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.

Related Policies and Procedures:
- Nondiscrimination and Equal Employment Opportunity
- Procedures Regarding Unlawful Harassment
- Gender-Based Misconduct Policy
- Procedures for Responding to and Resolving Complaints of Gender-Based Misconduct
- Violence Prevention

VIOLENCE PREVENTION

1.0 Policy

It is the policy of Caltech to provide a safe and secure environment for all members of the Caltech community and to prohibit all forms of violence on its premises or in any of its programs or activities. Caltech promotes measures aimed at reducing incidents of violence and the management of situations that may lead to violence. All members of the Caltech community shall cooperate to maintain a safe environment and shall comply with this policy.

2.0 Scope

2.1 Prohibited Conduct

Caltech does not tolerate violence, threats of violence, child abuse, child neglect, or stalking on any Institute premises or in any Institute activity or program. All weapons are banned from Institute premises and at Institute activities and programs as set forth below.

2.2 Definitions

Acts of violence include any physical action, whether intentional or reckless, that harms or threatens the safety of another individual at Caltech.

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.

Child abuse includes sexual or emotional abuse of a child, and physical injury inflicted on a child by another person, excluding injuries caused by accidental means.

Child neglect includes negligent treatment which threatens the child's health or welfare.

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. Course of conduct means two or more acts, including, but not limited to, acts in which the stalker directly, indirectly, or through third parties, by any action, method, device or means, follows, monitors, observes, surveils, threatens, or communicates to or about a person or interferes with the person's property. Reasonable person means a reasonable person under similar4 circumstances and with similar identities to the victim. Stalking that is sex or gender-based should be reported and will be handled pursuant to the Gender-Based Misconduct policy and applicable procedures. Stalking that is not sex or gender-based is covered by this policy.

Weapon is defined as a firearm, ammunition, BB or pellet gun, paintball gun, stun gun, compressed air gun or any replica firearm, martial arts weapon, fireworks, explosives, dangerous or highly flammable chemicals, dirk, dagger, ice pick, or knife having a blade longer than 2 1/2 inches (except for a knife or ice pick used for food preparation or consumption or for a lawful use in or around a residence), razor with an unguarded blade, razor blade, or box cutter (except for a razor, razor blade or box cutter for lawful use in a residence), or any object when used in a manner or under a circumstance that potentially may or does result in an act of violence or threat of violence.

An object otherwise defined above as a weapon is excepted when used for a lawful purpose within the scope of the person's employment or academic activities when approved by Caltech.

2.3 Reporting Violence

Any individual who experiences or observes a threat or act of violence, or a weapon on Institute premises or at an Institute activity or program must immediately notify Campus Security or JPL Protective Services Division, or law enforcement. An individual at a non-campus or non-JPL location must immediately notify local law enforcement.

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

If an individual becomes aware of behavior that they find concerning, the individual should notify one of the following individuals or offices:

Employee's supervisor/management
Campus Human Resources – EOD	626-395-8039
Dean of Students	626-395-6351
Dean of Graduate Studies	626-395-6346
Provost Office	626-395-6320
Assistant Vice President for Equity And Equity Investigations, Title IX Coordinator	626-395-3130
Campus Security	626 395-5000
Caltech Hotline (anonymous)	626-395-8787 or 888-395-8787
JPL Human Resources	818-354-4447
JPL Protective Services Division	818-354-3530
JPL Workplace Violence Hotline	818-393-2851
JPL Ethics Office	818-354-6338
JPL Ethics Help Line (anonymous)	818-354-9999 or 866-405-7536

Caltech will handle all reports of violence in a confidential manner, with information released as determined to be appropriate by Caltech. Managers are required to immediately report any violation or suspected violation of this policy to Caltech Security, JPL Protective Services Division, Human Resources, the Deans or the Provost, whether the violation is observed on Institute premises or at any Institute activity or program. Caltech policy prohibits retaliation against any faculty, staff, postdoctoral scholar, student, or third party who, in good faith, reports a violation or suspected violation of this Policy.

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.

2.3 Reporting Child Abuse or Child Neglect

A minor is anyone under the age of 18 years old (also referred to as a child).

A Mandated Reporter is an employee who is required by law to

make a report to the appropriate authorities whenever, in 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 or child neglect. All athletic coaches, including assistant coaches and graduate assistants involved in coaching are Mandated Reporters. In addition, Institute employees whose duties bring them into direct contact with children under 18 years of age on a regular basis or who supervise employees whose duties bring them into contact with children on a regular basis are Mandated Reporters as to child abuse or neglect occurring at Caltech or at an official activity of, or program conducted by, Caltech. Certain other professionals at Caltech, such as doctors, nurses and psychologists, are also Mandated Reporters.

Every member of the Caltech community who knows of or reasonably suspects child abuse or child neglect has a personal responsibility to report to Caltech Security or the JPL Protective Services Division immediately. Mandated Reporters have the additional responsibility to report immediately or as soon as practicably possible by telephone and to submit a written follow up report within 36 hours of receiving information concerning the incident to the LA County Child Protection Hotline (800) 540-4000 (or from out of state (213) 639-4500) or to the Pasadena Police Department 911 (for emergencies) or (626) 744-4501 (for non-emergencies), or to another local police department. A Suspected Child Abuse Report (SCAR) can be completed online (where the initial report was made to the LA County Child Protection Hotline) at https://mandreptla. org. Mandated Reports will be provided the opportunity for training by Caltech and must sign an "Employee Acknowledgement of Mandated Reporter Status."

2.4 Investigating Prohibited Conduct

Reports of conduct that may violate any aspect of this policy will be taken seriously, properly investigated and dealt with accordingly. Individuals who are found to have violated this policy may be subject to disciplinary action up to and including termination of employment, expulsion, or permanent removal from the premises. Additionally, when such acts potentially violate state or federal laws the matter may be referred to law enforcement agencies for investigation.

3.0 Resources

The Staff and Faculty Consultation Center and the Student Counseling Center at Campus or Empathia/Life Matters 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. In addition, training is available from Human Resources regarding violence prevention, public safety awareness, and child abuse. Contact information for these and other resources are:

Campus
  Staff and Faculty Consultation Center   626-395-8360
  Human Resources -EOD   626-395-8039

JPL
  Human Resources   818-354-4447
  Empathia/Life Matters   800-367-7474

Related Policies
  • Unlawful Harassment
  • Procedures Regarding Unlawful Harassment
  • Gender-Based Misconduct
  • Procedures for Responding to and Resolving Complaints of Gender-Based Misconduct

WHISTLEBLOWER POLICY

1.0 Policy

It is important to Caltech that employees disclose violations or potential violations of law or other 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 of employment or permanent separation from Caltech.

   It is Caltech's policy to comply with applicable laws and regulations, including California's whistleblower law protections provided under Labor Code Section 1102.5 and the whistleblower rights and remedies provided under 41 USC Section 4712, which are summarized at Enhancement of Employee Whistleblower. As employees of Caltech, each individual is responsible for making sure his or her conduct fully complies with all laws and regulations as well as Institute policies. Caltech expects employees with knowledge of specific acts that they reasonably believe violate the law or Caltech policy to disclose those acts to an appropriate Caltech official.

2.0 Reporting

An employee who becomes aware of any inappropriate or improper activity, or who believes they have been the subject of retaliation for making a good faith disclosure, is encouraged to contact their supervisor or one of the following offices: Human Resources, JPL Ethics Office, Audit Services and Institute Compliance (ASIC), or the Office of General Counsel. Anyone with questions or concerns regarding inappropriate or improper activities within Caltech 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
1200 E. California Blvd
MC 250-64
Pasadena, CA 91125

JPL Ethics Line:
(818) 354-9999 or Toll Free (866) 405-7536

STUDENT AFFAIRS POLICIES

Student Leadership Expectations

Graduate and undergraduate student leaders who are in either elected or appointed positions must be enrolled and in good standing with the Institute.

In addition to the Institute Policies listed above, there are a number of Student Affairs policies, procedures and guidelines on the student affairs website:
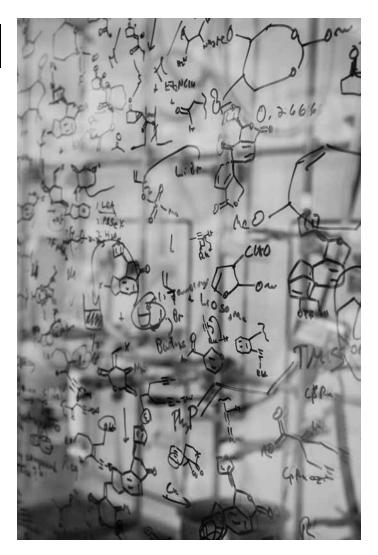
 • Alcohol and Other Drugs on Campus
 • Fire Safety
 • Firearms and Other Dangerous Materials
 • Good Samaritan
 • Hazing
 • Missing Students
 • Murals
 • Student Problem Resolution Process

For the text of the full policies, please see the Student Affairs website at studentaffairs.caltech.edu/policies.

Areas of Study and Research

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, the Center for Autonomous Systems and Technologies, 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 and design and control of autonomous systems. 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, dynamical systems, 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 activi-

ties 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.

- *Autonomous Systems and Technologies.* Interdisciplinary research in the expanding area of autonomous systems involves, but are not limited to, drones, robots, and spacecraft for use in science, exploration, and transportation. The research addresses sensing, control, vision, machine learning, and other emerging areas. Advanced drone research,

autonomous exploration, and swarm robotics will draw research from the full range of engineering at Caltech, the geological and planetary sciences division, and JPL.

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, and special-purpose flow facilities. 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.

The Center for Autonomous Systems and Technologies (CAST) contains an 85 ft. track for walking robots and a wholly enclosed 75,000 cubic foot aerodrome for drone testing which is the tallest of its kind. Environmental simulation is provided by a 100-square-foot wall comprised of 1,296 fans capable of generating wind speeds of up to 44 mph, along with a side wall of an additional 324 fans, all of which can be individually controlled to create a nearly infinite variety of conditions.

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.

Other assets include state-of-the-art electronic instrumentation and computer systems for real-time control of experiments, data acquisition, processing, storage, and 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, computational fluid dynamics, mathematics of data science, probability, random matrix theory, applied algebraic geometry and statistical inference, game and decision theoretic approaches to numerical approximation and learning, homogenization, multifidelity and multiscale analysis, and stochastic modeling, stochastic analysis, data assimilation and inverse problems. 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, continuous optimization, discrete optimization, statistical estimation, computational harmonic analysis, stochastic processes, signal and imaging processing, inverse problems, mathematical biology, large-scale scientific computing, mathematics of data science, and probability and random matrix theory, game and decision theoretic approaches to numerical approximation and learning, homogenization, multifidelity and multiscale analysis, and stochastic modeling and stochastic analysis, data assimilation, inverse problems, 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

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. Solid mechanics laboratories contain 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 coursework and research activities in solid state physics, electromagnetic wave propagation, optoelectronic 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 encouraged 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, advanced data analysis, laboratory astrophysics, and detector development. Projects and groups often bridge 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 astroinformatics; numerical general relativity; gravitational wave astronomy 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 as well as 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 Zwicky Transient Facility (ZTF). A much larger camera for this telescope, with a 47 square degree field, started operation in 2018, as the Zwicky Transient Facility (ZTF). The 60-inch telescope has been roboticized, and is used to monitor sources discovered by sky surveys.

In the 1990s, 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 growing 288 element long wavelength array which can image the entire sky every second, and a 6.1 meter telescope dedicated to observations 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, currently being repurposed to new experiments, 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 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. Caltech and the Jet Propulsion Laboratory (JPL) are also leading the development of the forthcoming SPHEREx mission, that will study the early stages of the universe, galaxy formation, and formation of planetary systems. There are numerous close connections with 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), which in 2015 made the historic first detection of gravitational waves from a black hole binary. Several other black hole mergers have been detected since then, as well as the first gravitational wave detection of a merger of two neutron starts in 2017. Numerous other discoveries are expected as the operations continue.

Astrophysics

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; energetic principles and molecular mechanisms that underlie the biogenesis of nascent proteins and maintenance of protein homeostasis in the cell; 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* (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, 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, 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 by evolution and design. Biocatalysis for sustainable "green" production of pharmaceuticals and specialty chemicals.
- *Fluid Mechanics and Transport Processes.* Mechanics of polymeric liquids, microstructured fluids, colloidal dispersions and suspensions, 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.

Areas of Study and Research

Applications to diagnostic and therapeutic problems in Global Health.

- *Electronic Materials and Devices.* Plasma processing of semi-conductors, 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 micro-electronic and photovoltaic applications. Nanoprobes, nanomechanics, nanofluidics. Crystallization in carbon nano-tube 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 and Soft Matter*. Structures, phase transitions, and dynamics of polymers, liquid crystals, surfactant solutions, gels, colloidal dispersions 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 chemistry program provides depth in the traditional areas of chemistry—organic and inorganic chemistry, chemical phys-

ics, 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

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 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. Managing the great complexity of useful systems requires a representation of computations amenable to both mathematical treatment and implementation. Whether the system is artificially designed (such as a multi-core processor), or naturally occurring (such as a molecule), the computer scientist formalizes the computation performed by the system and provides a systematic analysis of its requirements and formal guarantees on its outcomes.

Areas of Research

Research and advanced courses leading to the Ph.D. degree in computer science are concentrated in the following areas: quantum and molecular computation; parallel and distributed computation; theory of computation; information theory; machine learning and applications; computational economics; computer vision; computer graphics; discrete differential geometry; networking and power systems. 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). 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.

- *Robust Modeling of Physical Systems.* Caltech computer science 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.

- *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 by systematically defining and exploring their design space.

- *Theory.* A strong theoretical understanding is the necessary foundation for systematic design, analysis, and verification. The theory of computation focuses on deep mathematical problems, many of which have substantial technological impact. Theory in computer science at Caltech includes traditional areas such as complexity algorithms, theories of numerical computation, optimization, probability, and game theory. But theory is not relegated to a single group, and has strong connections to all disciplines represented at Caltech.

- *Networks & Distributed Systems.* Modern networks and distributed systems are undoubtedly the most complex and critical pieces of infrastructure that the world has created. This includes communication networks as well as power networks, social networks, cloud computing, and more. The massive scale and exponential growth of such networks presents unique algorithmic, computational, and economic challenges. Research at Caltech approaches these challenges through a combination of rigorous design, systematic analysis, and interdisciplinary collaboration.

- *Machine Learning.* In our increasingly data-rich world, it is more important than ever to develop principled approaches that can intelligently convert raw data into actionable knowledge. At Caltech, we take a broad and

integrated view of research in data-driven intelligent systems. The Decision, Optimization and Learning group brings together researchers from machine learning, optimization, applied math, statistics, control, robotics, distributed systems and human-computer interaction to form an intellectual core pertaining fundamental and applied research from statistical machine learning to statistical decision theory through optimization.

- *Interdisciplinary Research.* Computer simulations, modeling, and analysis are key enablers, allowing all fields of science to advance rapidly. Furthermore, insights into computational management of information helps us understand information processing issues in natural systems (from cells and neurons to financial markets and social networks) and build hypothetical models that advance our understanding of natural cognition. 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 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 libraries 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 devices 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, photonics, 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* (Emami, 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* (L. Wang, C. Yang)—Experimental research on imaging and extraction of information from biological targets through the use of light. Current areas of interest include optofluidics, wavefront shaping, wide field-of-view imaging, chip-scale microscopy, Fourier ptychographic microscopy, photoacoustic tomography, and compressed ultrafast tomography. More information can be found at www.biophot.caltech.eduand http://COILab.Caltech.edu

Areas of Study and Research

- *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.

139

- *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, graph signal processing, and other applications."
- *Distributed Information Systems* (Bruck)—Rigorous theoretical and experimental studies that explore the challenges and benefits of the physical implementation of modulation and coding schemes for flash memories, example include rank modulation and rewriting codes. We collaborate with

industrial partners to design the next generation flash memory systems; and with JPL, to enable nonvolatile memory solutions for space missions. In addition, we study distributed storage systems and develop RAID schemes with optimal rebuilding and secure schemes with optimal decoding.

- *High-Frequency 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.

- *Information Theory and Biological Evolution* (Bruck)—What is the primary mechanism for the evolution and diversity of DNA sequences? One possible answer (and arguably the prevalent one) is that diversity in DNA is due to random mutations. However, it is well known that more than 50% of the human genome consists of repeated sequences and that these repeated sequences are common in other species as well. We conjecture that diversity and evolution in biological systems is primarily achieved through replication mechanisms. We attempt to prove this conjecture by evaluating string replication systems from an information theory perspective, as well as study tandem duplication and interspersed duplication mechanisms.

- *Information Theory for Network Biology* (Effros)— Theoretical investigation of the design and implications of models for biological communications networks. Research involves the development of mathematical models of communicating components in biological systems (e.g., neurons in the brain), the application of information theoretic tools to understand the implications of such models, and the comparison of those implications to salient features of the studied networks as a means of testing their plausibility.

Areas of Study and Research

- *Integrated Biosensors* (Emami, Hajimiri, Scherer)—Use of integrated 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, performance 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 www.chic.caltech.edu and www.mics.caltech.edu/

- *Machine Learning and Artificial Intelligence* (Abu-Mostafa)— The Learning Systems Group at Caltech studies the theory, algorithms, and applications of Machine Learning (ML). The theory of ML uses mathematical and statistical tools to estimate the information (data and hints) needed to learn a given task. The algorithmic aspect of ML deals with how to train different models efficiently. The applications of ML are very diverse and continue to expand to every corner of science and technology. The group works on medical applications of ML, on e-commerce and profiling applications, and on computational finance, among other domains. These applications use the latest techniques of neural networks and other models, and often give rise to novel ML theory and algorithms.

- *MEMS/bioMEMS/OpticalMEMS/NEMS* (Tai)—We exercise MEMS, Micro- and nanotechnologies 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* (Marandi, Scherer, Tai)—The micro-/nanotechnology research at Caltech focuses on biomedical, electro-mechanical, and optical applications in the micro-/nanoscales. The effort is centered on the two separate clean room facilities—KNI Lab (www.kni.caltech.edu/facilities) for nanoscale research and the Caltech Micromachining Laboratory (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 nanoscale 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-/nanoscale sensing structures for various types of Raman spectroscopy, and energy-harvesting. All aspects of micro-/nanoscale 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* (Marandi, Scherer)—High-resolution lithography and dry etching allow the miniaturization of struc- tures 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; field emission vacuum electronic devices and circuits; 3D electrochemical contacts and bioelectronic composites; optofluidic systems; integrated microfluidic pumps, valves, and wireless sensors.

- *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.

Areas of Study and Research

- *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.

- *Nonlinear Photonics* (Marandi)—Experimental, theoretical, and numerical studies of photonic devices and systems with strong nonlinearities for development of new technologies for sensing, computing, information processing, and communications. We explore the frontiers of ultrafast optics, optical frequency combs, quantum optics, optical information processing, mid-infrared photonics, and laser spectroscopy. We use state-of-the-art laser systems, micro and nano fabrication tools and techniques, unconventional materials, and numerical and theoretical techniques. While the main goal is experimental realization of novel nonlinear photonic systems, techniques, and technologies, we also work on advancing the theoretical understanding of these systems as well as applying our solutions to real-life problems.

- *Quantum electronics, theory and devices* (Yariv)—The group is involved in theoretical, experimental, and fabricational exploration of devices and phenomena at the confluence of laser physics, classical optics, quantum optics, and quantum mechanics. Present area of investigation are:

  1. **Hybrid high coherence Si photonics semiconductor lasers.** Semiconductor lasers are the linchpins of communication and sensing applications. We have designed, fabricated, and are currently characterizing in our laboratory a new generation of hybrid Si/III-V lasers with quantum-limited Coherence (characterized by the Schawlow Townes linewidth) which is 1000X higher than current state-of-the art commercial lasers. A new generation of semiconductor lasers based on nonlinear optical interactions to further improve coherence is being investigated. The high coherence of the laser is a prerequisite to high communication data rates over the internet.

  2. **3D Lidar (Light Radar) Imaging.** We have recently applied optical phase-lock techniques to semiconductor lasers and demonstrated a controlled-chirp, swept frequency mode of operation. This swept mode is

Electrical Engineering

used in a 3D imaging system which we are developing applying chirped-radar methodology. The lasers take advantage of the long coherence length of the output field (See Quantum electronics, theory and devices above) to enable 3D imaging at long distances.

- *Silicon Photonics* (Emami, Hajimiri, Scherer)—Application of silicon integrated for photonics systems such as: high-speed data links, communication systems, imaging, projection, LIDAR, sensing, etc. This research area focuses on device, circuit, and system level development for these applications.
- *Smart Grids and Energy Supplies* (Chandy, Doyle, Low, 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* (Effros, 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 technol-

ogies 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 dynamics, and the dynamics of the Southern Ocean, and climates of other planets. 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.

Environmental Science and Engineering

- *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.

Laboratories for molecular geobiology provide capabilities for culturing, manipulating, and studying a wide range of environmental microbes, including anaerobes. 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 phi-

losophy 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, and philosophy of mind, psychology and neuroscience. In addition to survey courses we offer courses on more focused topics, including causality, probability, quantum mechanics, space-time, free will, consciousness, and on ethical questions raised by modern science and technology.

Visual culture at Caltech encompasses the study of art history, film, media and scientific images. Students work to gain visual literacy, and to understand both the history of images humans may have been looking at for hundreds or even thousands of years, and the provenance, location and nature of the images we see now in our every day lives. Some visual culture 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.

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

A variety of courses in music, writing, and in foreign languages, literature, and culture are also available.

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 and philosophy of mind, with particular research foci in philosophy of physics, causation, probability and decision theory, and the philosophy of neuroscience and free will.

Faculty research in visual culture focuses on a wide variety of time periods, geographic locations and media forms but has in common a careful attention to the conditions under which objects are made, the ways in which they circulate, and the reactions they inspire in audiences.

INFORMATION AND DATA SCIENCES

The information and data sciences are concerned with the acquisition, storage, communication, processing, and analysis of data. These intellectual activities have a long history, and Caltech has traditionally occupied a position of strength with faculty spread out across applied mathematics, electrical engineering, computer science, mathematics, physics, astronomy, economics, and many others disciplines. In the last decade, there has been a rapid increase in the rate at which data are acquired with the objective of extracting actionable knowledge—in the form of scientific models and predictions, business decisions, and public policies. From a technological perspective, this rapid increase in the availability of data creates numerous challenges in acquisition, storage, and subsequent analysis. More fundamentally, humans cannot deal with such a volume of data directly, and it is increasingly essential that we automate the pipeline of information processing and analysis. All areas of human endeavor are affected: science, medicine, engineering, manufacturing, logistics, the media, entertainment. The range of scenarios that concern a scientist in this domain are very broad—from situations in which the available data are nearly infinite (big data), to those in which the data are sparse and precious; from situations in which computation is, for all practical purposes, an infinite resource to those in which it is critical to respond rapidly and computation must thus be treated as a precious resource; from situations in which the data are all available at once to those in which they are presented as a stream.

As such, the information and data sciences now draw not just upon traditional areas spanning computer science, applied mathematics, and electrical engineering—signal processing, information and communication theory, control and decision theory, probability and statistics, algorithms—but also a range of new contemporary topics such as machine learning, network science, distributed systems, and neuroscience. The result is an area that is new, fundamentally different that related areas like computer science and statistics, and that is crucial to modern applications in the physical sciences, social sciences, and engineering.

The Information and Data Sciences (IDS) option is unabashedly mathematical, focusing on the foundations of the information and data sciences, across its roots in probability, statistics, linear algebra, and signal processing. These fields all contribute crucial components of data science today. Further, it takes advantage of the interdisciplinary nature of Caltech by including a required set of application courses where students will learn about how data touches science and engineering broadly. The flexibility provided by this sequence allows students to see data science in action in biology, economics, chemistry, and beyond.

In addition to a major, the IDS option offers a minor that focuses on the mathematical foundations of the information and data sciences but recognizes the fact that many students in other majors across campus have a need to supplement their options with practical training in data science.

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.

INTERDISCIPLINARY STUDIES PROGRAM

Interdisciplinary studies offer an educational alternative for under-graduates whose goals cannot be satisfied with a normal under-graduate option. The student gathers a two-person faculty commit-tee, representing at least two divisions of the Institute, and choos-es 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 interdisci-plinary 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 305.)

MATERIALS SCIENCE

Materials scientists study relationships between the properties of materials and their internal structure, and how this structure can be controlled. Our multidisciplinary faculty, students, and postdoctoral scholars create new materials and take rigorous approaches to understand and control the properties of materials and their inter-nal structure. From batteries and solar cells, to electronic devices and micro- and nano-, our department is at the forefront of scien-tific discovery and new technologies.

Areas of Research

The current areas of research by the materials science faculty include a broad range of materials, some far removed from their equilibrium thermodynamic states. Examples of such materials include metallic glasses, thin films, two-dimensional solids, quan-tum materials, porous and architected solids, energy-storage mate-rials, nanostructured materials, and materials for photovoltaics and electronic devices. The physical characteristics of interest span a wide range of mechanical, thermodynamic, electrical, magnetic and electrochemical properties.

Physical Facilities

Research by the faculty, graduate students, and advanced under-graduates 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 nano-characterization tools, such as focused ion beams (FIB), scanning electron micro-scopes (SEM), a nanoprobe, and a transmission electron microscope (TEM). Material-preparation facilities include equipment for additive manufacturing, 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 addi-tion 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, 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 is housed in the Ronald and Maxine Linde Hall of Mathematics and Physics and the W.K. Kellogg Radiation Laboratory. In addition to offices for the faculty and graduate students, there are classrooms, conference rooms, discussion areas, a lecture hall, and a lounge for informal gatherings of the students and staff. The mathematics library is housed nearby in the Sherman Fairchild 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 thermocapillary 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

The Andrew and Peggy Cherng Department of 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
- *Affordable Medical Devices and Technologies* (Gao, Gharib, Hajimiri, Ismagilov, Pickar, Yang). Chairs for children with cerebral palsy, bed-sore mitigation, toxic material filters, saliva-based diabetes tests, handheld diagnostic devices, and remote medical tracking systems. Devices which provide freedom from disability.
- *Biomaterials* (Gradinaru, Grubbs, Greer, Ismagilov, Shapiro, Tai). Biocompatible medical materials, nanoscale-engineered smart materials, device-tissue interface, and cell-material interactions.

- *Biomechanics & Bio-Inspired Design* (Burdick, Colonius, Gao, Gharib, Gradinaru, Shapiro). Bio-inspired self-propulsion technologies, control systems, optimization techniques, shape morphing, cardiovascular mechanics, biomolecular nanomechanics, and muscle and membrane mechanics.
- *Medical Diagnostic, Monitoring, and Therapeutic Implants* (Emami, Gao, 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.
- *Medical Diagnostic and Monitoring On-Chip Devices* (Emami, Hajimiri, Ismagilov, Scherer, Tai, and Yang). Magnetic spectroscopy, bioassay, and drug-screening platforms, micro-PCR and sequencer, and on-chip bio-sensors.
- *Medical Imaging and Sensing* (Colonius, Emami, Faraon, Gao, Gharib, Gradinaru, Greer, Hajimiri, Scherer, Shapiro, 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 spectroscopy, photoacoustic tomography, thermoacoustic tomography, optical time reversal (wavefront shaping/engineering), compressed ultrafast photography, holographic microscopy, non-invasive label-free biomedical imaging and magnetic resonance imaging, wearable biosensors.
- *Medical Nanoelectronics* (Emami, Gao, Hajimiri, Scherer). Integrated nanoelectronics and circuits for medical applications, extremely low power medical electronics and sensors, high bandwidth wireless communication devices, self-healing circuits and systems, on-chip tera-hertz sources, and systems-on-a-chip.
- *Micro/Nano Medical Technologies and Devices* (Burdick, Emami, Faraon, Gao, Gharib, Greer, Hajimiri, Ismagilov, Scherer, Shapiro, Tai, Wang, Yang). Biochips, bio-MEMS/NEMS, micro-/nano-fabrication, holographic microscopy, and photoacoustic microscopy for medical applications.
- *Nano & Micro Fluidics* (Gao, Gharib, Ismagilov, Tai). Micro-/nano-fluidics, drug delivery, and physiological machines.
- *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.
- *Wireless Medical Technologies* (Emami, Hajimiri, Gharib, Scherer, Shapiro, Tai). Wireless communications through

skins and tissues for medical electronic implants, electro-
grams, wireless power transfer, and biotic/abiotic interfaces.

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 geo-
chemical 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 geo-
sphere, 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 tem-
poral 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 chal-
lenges 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 behavior.

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 discovering new particles and interactions physics beyond the Standard Model (BSM) complemented by precision measurements of SM processes. Experimental efforts employ hadronic colliders and electron, muon, and neutrino beams at several international facilities. Current experiments include:
  ~ CMS searching for dark matter and other new particles and new symmetries up to the mass scale of several TeV at the Large Hadron Collider at CERN
  ~ the NOvA and DUNE long baseline experiments at Fermilab,

studying the pattern of masses, mixing and CP violation in the neutrino sector

~ the Mu2e experiment, searching for physics beyond thE standard model in charged lepton flavor violation

~ a nascent effort to search for accelerator production of dark matter called LDMX

~ the long-running SuperCDMS effort to directly detect scattering of galactic dark matter with normal matter.

- *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.

- *Condensed-Matter Physics.* Areas of interest include correlated electron systems, topological quantum systems, 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.

- *Experimental Atomic/Molecular/Optical Physics.* Experimental atomic, molecular, and optical (AMO) research at Caltech focuses on controlling and understanding complex quantum systems for a wide variety of scientific goals. Current experiments include building arrays of ultracold atoms to study quantum information, metrology, many-body physics, and simulation of condensed matter systems; precision measurements in cold and ultracold polar molecules to search for fundamental symmetry violations; engineering atom-light interactions in photonic crystals; quantum physics of mechanical devices, hybrid superconducting quantum circuits, and optomechanical sensors; neurophotonics and neuromolecular sensing; development of quantum networks and communication and addressing fundamental questions in quantum information. Many of these research strands are collaborative efforts supported by the Institute for Quantum Information and Matter.

- *Nuclear Physics.* The interests of the nuclear group focus on performing precision measurements to search for new physics beyond the Standard Model. In particular, precision measurements of free 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.
- *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 millimeter/submillimeter astronomy group, with collaborators at the Jet Propulsion Laboratory, studies the solar system, star and planet formation, the interstellar medium, galaxies, galaxy clusters, and the epoch of reionization using data from the Caltech Submillimeter Observatory (CSO) and other facilities. Future-oriented programs include the development of new superconducting detector technologies and instruments for use at these wavelengths, also in collaboration with JPL, and an effort to move the currently idle CSO to a new, more sensitive site.
    - ~ The Galactic compact objects astrophysics group studies black holes, neutron stars, and white dwarf systems, including gravitational wave sources detectable by future space missions such as LISA. The group uses telescopes at Palomar, Kitt Peak and the Keck Observatory, as well as the radio telescopes of the NASA Deep Space Network.
- *Theoretical Astrophysics.* The TAPIR (Theoretical Astrophysics Including Relativity) group carries out research on an ever-changing list of topics, including planets; stars, neutron stars, black holes and their interactions; gravitational-wave astrophysics; cosmology; the formation of stars and galaxies; and numerical and analytical 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 and large scale structures 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

  gravitational-wave signals from sources such as coalescing black holes and neutron stars.

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 (currently idle), and the Laser Interferometer Gravitational-wave Observatory (LIGO).

SCIENCE AND ENGINEERING COMMUNICATION

The Engineering and Applied Science (EAS) Division offers a program of study in Scientific and Engineering Communication that prepares students to engage with a variety of audiences and effectively communicate scientific topics. In order for engineering graduates to excel in their chosen field, they need to develop oral, written, and media communication skills, and an ability to work with a variety of stakeholders including industry leaders, policy-makers, and academics. Courses in Scientific and Engineering Communication (SEC) provide opportunities for students to experiment with a variety of communication genres and in diverse environments. The program is characterized by cross-disciplinary study and authentic practical experiences in scientific communication and advocacy.

SOCIAL AND DECISION NEUROSCIENCE

The Institute offers an interdisciplinary program of study in Social and Decision Neuroscience that prepares students to conduct research on the neurocomputational basis of decision-making and social interactions. In order to carry out cutting-edge research in this area, students need to acquire in-depth understanding of computational modeling, statistical methods, systems neuroscience, neural measuring methods such as fMRI, EEG or single unit recordings, as well as adequate understanding of related methods and results from the social sciences. The program is designed for students seeking faculty jobs in Neuroscience, Psychology, Marketing, Economics, Political Science or Finance, or industry positions in the technology, data science, and finance fields.

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 choice in animals and humans.
- Computational and neurobiological basis of economic and political decision making.
- Neurocomputational basis of emotion and the impact on cognition and behavior.
- Neurobiological basis of social behavior in human and animal models.
- Neurobiological basis of moral judgment and decision-making.
- Applications of neuroscience to economics, finance, and political science.

Physical Facilities

Research is conducted 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.

SOCIAL SCIENCE

The Caltech PhD program in Social Science is highly interdisciplinary, integrating economics, political science, quantitative history, econometrics, and finance. It makes extensive use of mathematical modeling, laboratory experiments, and econometric techniques.

Research in the social sciences program at Caltech strongly emphasizes the understanding and analysis of the relationships between individual incentives, collective behavior, political and economic institutions, and public policy.

Areas of Research

Experimental Economics and Political Science. Caltech social scientists were among the early pioneers in the field of laboratory experimentation and Caltech has maintained a strong leadership position and research presence in the field ever since. Examples of the kinds of laboratory studies the faculty are engaged in include the behavior and design of auctions and market-like mechanisms, public goods provision and related topics in public economics, the economics of networks and matching, decision theory, inter-personal bargaining, behavioral economics, committee decision making, and electoral competition. Many of our faculty engage in laboratory experimentation as part of their research agendas in economics and political science (Agranov, Camerer, Echenique, Ordeshook, Palfrey, Plott, Saito, Shum) 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 (see Facilities) in the William D. Hacker Social Science Experimental Laboratory (SSEL) and the Laboratory for Experimental Economics and Political Science (LEEPS). The real world provides another setting for experimental research outside the laboratory, and Caltech social scientists have conducted field experiments involving a wide variety of topics, ranging from decision making in organizations, social networks, and the behavior of different cultural groups ranging from college students, to urban Americans to African villagers.

- *Economic Theory and Game Theory.* Caltech has a strong research group in economic theory, which, together with rigorous training in statistics and econometrics forms the backbone of the core curriculum for the PhD program. Theoretical research at Caltech has played a key role in the design and practical implementation of new institutions that more efficiently allocate scarce resources and provide public goods. Some of this work has had important public policy applications. Prominent examples include the design of FCC auctions to allocate the electromagnetic spectrum for telecommunication, and the market for allocating and trading permits for pollution emissions in the Los Angeles basin. Much of this theoretical design research is complemented by experimental studies that provide a testbed for competing designs. There is an active group of faculty and

graduate students working in the areas of the optimal design of contracts and markets (Cvitanic, Doval, Echenique, Plott), the economics of information (Doval, Pomatto, Tamuz), decision theory (Border, Echenique, Pomatto, Rangel, Saito), game theory (Doval, Echenique, Palfrey, Pomatto, Saito, Tamuz) and matching (Doval, Echenique). There are several active programs for interaction between our theory faculty in the social sciences and the faculties of computer science and applied mathematics. This is formally organized around two interdisciplinary centers, the Lee Center for Advanced Networking and the Social and Information Science Laboratory (SISL), with the latter offering a bi-weekly seminar coordinated between the computer science department and the social sciences faculty and featuring speakers in economics, computer science, game theory and related disciplines. There are many informal connections that reinforce the formal connections, including research collaborations between faculty and graduate students in these different areas.

- *Political Economy and Political Science.* Caltech has a long tradition of strength in research that spans the boundary of the Economics and Political Science disciplines. Research in political economy at Caltech continues to be a major strength of the program and provides a natural bridge that unites the faculty in economics, political science, and quantitative history. The focus of research in political economy and political science at Caltech emphasizes rigorous theoretical modeling drawing heavily upon techniques from economic theory and game theory, combined with empirical studies using highly sophisticated quantitative analyses of a wide variety of data sources: experimental, survey, field, voting, and historical data. Ongoing political economy research areas of the current faculty include: the interacting forces of bargaining, voting, and communication in committees, legislatures, bureaucracies, and assemblies (Agranov, Gibilisco, Hirsch, Katz, Lopez-Moctezuma, Palfrey, Plott); the Voting Technology Project, a joint Caltech-MIT research venture, established in 2000 to evaluate and improve the performance and reliability of U.S. balloting technology, registration systems, election administration, redistricting, and election law (Alvarez, Katz); political forces affecting judicial behavior (Hirsch, Kousser, Shum), strategic voting in multicandidate and multi-stage elections (Alvarez, Kiewiet, Palfrey, Plott), the politics of inequality and redistribution (Agranov, Palfrey) and several areas of comparative and international politics, including studies of the causes and consequences of corruption, domestic unrest, and international conflict (Ensminger, Gibilisco, Lopez-Moctezuma).
- *Financial Economics.* Caltech has built a small but very

active research group in finance. The researchers in this group are working on a range of topics in mathematical finance (Cvitanic), empirical studies of venture capital and entrepreneurship (Ewens), asset pricing (Cvitanic, Jin, Plott, Roll), dynamic contracting (Cvitanic), and behavioral finance (Camerer, Jin, Plott). There is a regular seminar series in finance that features distinguished researchers from around the world. Caltech faculty outside the finance group itself are also engaged in empirical research in financial economics. These include experimental studies of asset markets (Camerer, Palfrey, Plott), interest rate policy making by the Federal Open Market Committee (Lopez-Moctezuma), and online credit markets (Xin).

- *Behavioral Economics.* Research in behavioral economics at Caltech overlaps all of the above groups. Laboratory experimental research discovers interesting behavioral anomalies and can also test theoretical models designed to account for such anomalies. On the theoretical side, much of the game-theoretic and decision-theoretic research at Caltech is motivated by experimental observations, leading to extensions or modifications of standard models. These extensions in turn suggest experimental designs that are then implemented in the laboratory by our faculty and graduate students. Faculty research in political behavior (Alvarez, Katz, Kiewiet) and behavioral finance (Camerer, Jin, Plott) are complementary and add strength more generally to understanding social behavior. We also have on our faculty a small but very active group conducting research at the boundary of biology, psychology, and the social sciences (Adolphs, Camerer, Mobbs, O'Doherty, Rangel). This group offers a separate PhD option focused on the behavioral neuroscience of decision making (see the catalog entry for "Social and Decision Neuroscience"). Utilizing fMRI brain-imaging, eye-tracking, and other biological measurement technologies, this group, often in collaboration with other social science faculty and graduate students, has begun to explore the neural foundations of decision making in individual choice, game theoretic, and market settings.

- *Quantitative History.* Just as with the theoretical, experimental, and empirical work using contemporary, historical research conducted at Caltech employs mathematical modeling and sophisticated statistical techniques to attack a wide range of historical questions. Historical research conducted at Caltech addresses questions that cut across economics, political science, political economy, and even finance, often combining archival work with state-of-the art statistical techniques. These include the development of capital and credit markets in Europe (Hoffman, Rosenthal), the impact of historical and contemporary racial discrimina-

tion in the United States (Kousser), the evolution of wealth distribution from 1800 to the present (Rosenthal), the causes of recurrent financial crises in capitalist economies (Hoffman, Rosenthal, and the determinants of economic and technological growth.

- *Applied microeconomics and econometrics.* Empirical research in social science blends creative collection and analysis of field data with rigorous application of tools and methods from econometrics and statistics. We offer courses and supervise students in these areas. A number of faculty members specialize in empirical work in a number of fields, including finance (Ewens, Jin, Xin), industrial organization (Shum, Xin), political economy (Alvarez, Gibilisco, Katz, Kiewiet, Lopez-Moctezuma, Sherman, Shum), and behavioral economics (Camerer, Jin). Methodological areas of specialization include econometrics (Sherman, Shum, Xin), causal inference (Alvarez, Katz, Sherman, Shum), machine learning (Alvarez, Katz, Xin), and Bayesian statistics (Katz).

Physical Facilities

Caltech has two state-of-the-art onsite laboratories for experimental research in economics, political science, game theory, decision theory, and financial economics: The Laboratory for Experimental Economics and Political Science (LEEPS, established 1987) and The Hacker Social Science Experimental Laboratory (SSEL, established 1998).

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 sequen-

tial, 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.

Section Three

Information for Undergraduates

Undergraduate Information

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 www.admissions.caltech.edu. Students are encouraged to apply online through the Common Application, the Coalition Application, or the QuestBridge program. 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 or ACT
  SAT Mathematics Level 2
  One of the following SAT subject tests: Biology (molecular or ecological), Chemistry, or Physics
  TOEFL (for international applicants)

  Information regarding the College Board examinations can be found online at www.collegeboard.org, or by contacting the College Board, 250 Vesey Street, New York, NY 10218; (212) 713-8000. For ACT, 500 ACT Drive, P.O. Box 168, Iowa City, IA 52243-0168; (319) 337-1270; 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 teacher evaluations and a Secondary School Report are required. One evaluation must be from a math or science teacher, and one evaluation 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 mid-March.

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.

Residency Expectation

Freshman students have long been required to live on campus in undergraduate housing for their first academic year. With the opening of the Bechtel Residence, the residential experience is now extended to a full four years for undergraduate students, beginning with the class of 2022 (that is, freshmen matriculating in 2018). Undergraduate housing includes the eight houses (Avery, Blacker, Dabney, Fleming, Lloyd, Page, Ricketts, Ruddock), and the Bechtel Residence and Marks House and Braun House. Requests for exceptions from a four-year residency expectation should be submitted to the Office of Residential Experience, and must be approved by the Dean of Undergraduate Students and the Vice President for Student Affairs.

New Student Orientation

All freshmen, transfer, and exchange students are expected to attend the New Student Orientation as part of the regular registration procedure. Orientation takes place the week prior to the beginning of classes. Faculty members, staff and upperclass student leaders participate help to introduce new students to the Caltech community. The orientation period provides an opportunity for

new students to become acquainted with the campus, the Honor System, and other aspects of life at Caltech. In addition, they 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 234; can be taken freshman or
        sophomore year)
Sophomore courses:
    Physics 2 abc or Physics 12 abc
    Additional laboratory science
    Humanities and Social Science electives

Note: Mathematics 3 is not required for the core curriculum, but may be required for a specific option.]

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 school instruction in English 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. The transfer applicant will submit course descriptions, syllabi, and final transcripts to the Registrar who will present the material to the faculty for evaluation.

Faculty members review each course submitted for credit on an individual basis. It is sometimes not possible, therefore, to answer questions regarding the acceptability of course work taken elsewhere. Before the student is admitted, transfer students will work through Admissions to obtain a pre-evaluation estimate. 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.

- A Caltech undergraduate degree is based on a four-year residential experience (study abroad included) in which students have the time to explore their academic interests in a deep and rigorous way. Students who are admitted as transfer students or 3/2 students may be granted advanced standing and term 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.
- 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 www.admissions.caltech.edu. Students should apply online through the Coalition Application. 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, Hima Vatti, who can be reached at TitleIX@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)	Ohio Wesleyan University (OH)
Bryn Mawr (PA)	Pomona College (CA)
Grinnell College (IA)	Reed College (OR)
Haverford College (PA)	Spelman College (GA)
Mt. Holyoke College (MA)	Wesleyan University (CT)
Oberlin College (OH)	Whitman College (WA)
Occidental College (CA)	

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 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 AND STUDY AWAY

Study abroad or away allows students to experience life in other countries and regions of the United States, 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 or Study Away. 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 www.fasa.caltech.edu.

UNIVERSITY OF CHICAGO STUDY AWAY PROGRAM

Our newest program is an exchange with the University of Chicago. Students will spend the fall term at the University of Chicago and live in a University of Chicago hall of residence in a single room. Students are required to take at least two classes (18 units) in classes that will fulfil option requirements. Students take a maximum of 4 classes and can take up to 2 classes in the humanities or social sciences. A number of Chicago's graduate schools will be visiting undergraduates to take class. This is restricted to one class total, which is part of the maximum of 4 classes. This requires a petition that is executed after a student is nominated to the exchange and accepted by the University of Chicago and within the timeframe designated by the University of Chicago. Information on which graduate schools allow this is available in the exchange application materials.

A minimum GPA of 3.5 is required to apply. Eligible sophomores and juniors interested in either the fall or winter term should apply by the January deadline for the fall term of the next academic year. Further information, including application procedures, more about the University of Chicago exchange, and the exact deadline date, is available from the Fellowships Advising and Study Abroad Office at www.fasa.caltech.edu. More information about the University of Chicago can be found at www.uchicago.edu.

Students are required to attend the fall orientation for which a fee is charged, ~$400 to $500. The orientation takes place the week prior to the start of the fall quarter. Since the University of

Chicago is on a quarter system, their fall term correponds closely to Caltech fall term dates.

Please see the Financial Aid section for details on applying for and eligibility for financial aid related to study away. Students who receive financial aid should list supplemental charges and travel in their aid application.

STUDY ABROAD PROGRAMS

CAMBRIDGE SCHOLARS PROGRAM

The Caltech Cambridge Scholars Program offers qualified juniors and seniors the opportunity to spend the 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, or engineering sciences to take classes within the tripos, i.e., subject, offered by that department. Students can only take courses in one tripos subject, but can usually take classes from more than one part of the tripos in that subject. Students will find more information on the tripos structure and Cambridge University in the Fellowships Advising and Study Abroad Office or at 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 in some subjects. For their classes, students receive a minimum of 36 Caltech units that can be used to fulfill option requirements 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 3.6 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, and the exact deadline date, is available from the Fellowships Advising and Study Abroad Office at www.fasa.caltech.edu. Students can find more information about Cambridge at www.cam.ac.uk.

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 (UCPH) or the Danish Technical University (DTU), both universities in the Copenhagen metropolitan area. At UCPH 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 UCPH or DTU as their 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 may be 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 UCPH live in a UCPH 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 UCPH 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 (European Credit Transfer System) and at least two classes (18 Caltech units) must get option credit of some type. All students take a class in the Danish language offered at UCPH. Students attending Copenhagen University are required to take a course in Danish culture and two Block 1 and one Block 2 class. Students attending DTU may elect to take a class from the Danish Culture series (monarchy, film, Vikings, etc.) if it fits their schedule and they do not exceed 30 ECTS. units combined with their DTU classes and Danish language class at UCPH.

All upper-level undergraduate or beginning graduate-level courses at UCPH 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 technolo-

gy 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 UCPH or DTU depending on their admitting university. This course is not required, but as noted, 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: www.fasa.caltech.edu. Go to www.dtu.dk or www.ku.dk for further information on DTU or UCPH.

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. A minimum 3.0 GPA is required.

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, often referred to by the nickname "L'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 one academic area called an approndisement. The subjects are engineering, computer science as well as the sciences, e.g., chemistry, physics, environmental sciences (GPS students) and mathematics. Students can also take one class in the social sciences and humanities if their schedule permits. All students take a French language class. Classes are taught in French or English based on the

instructor's preference. However, *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 the fall term 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.

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 usually 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 (CSE). 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, are allowed to take 40 credits in economics in order to fulfill BEM or economics option requirements if the student also takes 40 credits in the College of Science and Engineering.

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 two classes in the department is closest to their option and which will serve as the student's admitting department. The two required classes (18 Caltech units) varies from 20 to 40 Edinburgh credits based on whether the two classes are 10 or 20 credit classes each. Students can take all of their classes in their admitting department or can take classes in other CSE departments provided they meet requirements. Students can take 20 credits (one course) in the College of Arts Humanities and Social Sciences or up to two 40 credits in this college if they take 40 credits in the College of Science and Engineering. Note that 60 credits (4 classes) is the standard course load, but most Caltech students take 70 to 80 credits. Note that at least 36 Caltech units must be taken, I.e., 4 classes/60 credits.

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: 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 a fall term 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 exchange student orientation the week before the semester begins. Students also attend a new student orientation the first week of the semester. 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 lon-

ger 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 at least 50% 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 in the STEM subjects. Students cannot be admitted into humanities or social science departments.

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, the the Slade School of Design, which do not admit visiting students, even those with majors in English literature or the arts. 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 15 UCL credits. Caltech students must take 60 UCL credits during their semester at UCL. This would be equivalent to 36 Caltech units unless a class is equivalent to a 12-unit Caltech class. UCL classes fulfill option credit, humanities or social science credit or general 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.

Students are only allowed to take Year One classes in the economics department. Students can take higher level economics classes in the School of Eastern European and Slavonic Studies.

A minimum 3.4 GPA is required to apply and some departments such as Computer Science (3.9) or the Biological Sciences (3.5) require a higher GPA. Advice on this can be obtained from Caltech's study abroad office.

Certain departments at UCL will not admit fall only exchange student. For this year the subjects include, mathematics, statistical sciences, physics, all engineering sciences except for mechanical engineering, which does admit fall only students.

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 (Semester 2) at the University of Melbourne, which is located in the vibrant 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. Halls of residence have either an apartment or suite setup and offer that vary by hall assigned 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, computer lab, and laundry. Students share a suite or apartment with other students.

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 to fulfill option credit, humanities or social science credit, or general credit 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.

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 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 in full or worked out a satisfactory payment plan with the Bursar's Office.

Any student who has not completed both parts of registration within one week after the first day of classes will be removed from the Institute rolls. The Institute can place a hold on a student's registration in a variety of circumstances including any failure to comply with Institute requirements.

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 leave.

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.

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 achiev-

ing 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. Any requests to add research after June 1 must be submitted as a Late Add petition to the Undergraduate Academic Standards and Honors Committee (UASH) as well as be approved by the Division Chair. 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.

UNDERGRADUATE STUDENT LEAVES OF ABSENCE

Voluntary Leaves

Personal Leaves

A student may request a voluntary leave of absence for personal reasons (personal leave) by submitting a written petition via completion of the undergraduate leave form. International students should consult with the International Student Programs Office regarding visa implications prior to submitting the leave petition.

The dean or designee may grant a personal leave provided (a) the student is in good standing, in other words does not have to meet special academic or disciplinary requirements as a result of reinstatement, (b) the leave is for one year or less, although special circumstances can be considered for a longer leave, and (c) the leave extends over a period that includes at least one full term.

A student on personal leave may not attend classes, live in Institute housing, participate in Institute programs, use Institute facilities, work on campus, or use student services such as the Health and Counseling Services, Center for Diversity, Career Services, or the Hixon Writing Center during the leave, unless approved in writing by the dean or designee.

A petition to return from a personal leave should be submitted six (6) weeks before the first day of the term for which the student intends to return.

Medical Leaves

If a student is unable to complete their coursework due to medical reasons, the student may petition for a medical leave of absence by submitting a written petition via completion of the undergraduate leave form. The dean or designee may grant a leave for medical reasons, provided the petition is recommended by the director of Health and Counseling Services or designee. International students should consult with the International Student Programs Office regarding visa implications prior to submitting the medical leave petition.

Medical leaves are expected to extend over a period that includes at least one full term, although special circumstances may be considered for approval of a shorter leave upon the recommendation of a student's treatment team.

Students must provide documentation of the need for the leave by a licensed treatment provider. Students may be required to sign a release of information form authorizing their treatment provider to communicate relevant medical information to representatives within Health and Counseling Services and the Dean's Office to facilitate evaluation of the need for the leave and to determine appropriate conditions associated with the leave, and establishing expectations for return from the leave.

The Institute may impose conditions on return from a medical leave, which may include confirmation from the student's health care provider that the student is following the recommended course of treatment, the student's consent for the provider to discuss the student's condition or progress during the leave with Caltech officials, including representatives of Health and Counseling Services and the Dean's Office, and an independent evaluation of the student's readiness to return by a qualified medical professional. Certain conditions of return will be specified at the time of the leave approval.

A petition to return from medical leave must be submitted six (6) weeks before the first day of the term for which the student intends to return. The return process includes an interview with the director of Health and Counseling Services and the submission of a completed return from medical leave and provider recommendation forms. Students are expected to sign a release of information form authorizing their treatment providers to communicate with Caltech, including representatives of Health and Counseling Services and the Dean's office to determine readiness to return and recommendations for reasonable accommodations. Final approval of the petition is the responsibility of the dean or designee.

A student returning from a leave for medical reasons will maintain the same academic standing that they had previously—i.e., if on academic probation, the student will remain on probation upon return from leave. Additional information and resources regarding medical leave, including financial and transcript implications, can be found at deans.caltech.edu.

While on Medical Leave

It is the expectation that a student on medical leave will focus on receiving treatment to manage the condition(s) that precipitated the leave. A student on medical leave may not attend classes, live in Institute housing, participate in Institute programs, use Institute facilities, work on campus, or use student services such as Health and Counseling Services, Center for Diversity, Career Services or the Hixon Writing Center during the leave, unless approved in writing by the dean or designee.

Pregnancy Leave

Consistent with Caltech policy and the requirements of Title IX, students who are unable to complete their coursework or other course of study for a period of time due to a pregnancy, childbirth and related medical conditions are eligible for a medical leave of absence. Students who are pregnant or who have recently given birth are also eligible for reasonable accommodations.

A pregnant student who wishes to take a medical leave should submit a completed petition and to the Office of Undergraduate Students after obtaining a recommendation from the director of Health and Counseling Services. Medical documentation from the student's treating medical provider is required.

The Institute also provides reasonable accommodations to pregnant students consistent with federal and state law. Reasonable accommodations may include allowing pregnant students to maintain a safe distance from hazardous substances, allowing them to make up tests and assignments that are missed for pregnancy-related reasons or excusing of absences that are medically necessary.

Bonding

An enrolled student in good academic standing who chooses to take a leave of absence because of the birth of his or her child may request a bonding leave by submitting a completed petition form to the Office of Undergraduate Students for approval.

Involuntary Leave

The dean or designee may determine that it is necessary to place a student on an involuntary leave in a variety of circumstances, including when a student demonstrates behavior that poses a threat to health or safety, causes significant disruption to the Caltech community, for the personal safety or welfare of the student involved, as an interim measure, or as a result of a disciplinary action.

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 Caltech 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 reasonable accommodations, resources and staffing that the Institute can reasonably be expected to provide for the student's well-being.

Review and Decision Process

If the conduct has been the subject of an investigation or review under an Institute process or procedure, the dean will consider the findings and conclusions reached in that process. In other circumstances described above, in making an informed decision to place a student on involuntary leave, the dean will conduct an individualized assessment and consider relevant information including information provide in a timely manner by the student.

The dean may consult with other Institute personnel, including but not limited to, security and residential life personnel, staff, faculty, and other individuals or departments. If appropriate and feasible, the dean may seek cooperation and involvement of parents or guardians of the student.

Medical information, including medical information provided in a timely manner by the student, may be considered if the behavior is associated with a physical or mental condition. In appropriate cases, the dean may consult with the director of 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 risk 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. The dean may stipulate conditions that must be met before the student may return. An involuntary leave may be a permanent separation from the Institute (i.e. expulsion); for a specific duration or until certain conditions have been met. If the involuntary leave is not a permanent separation, the student will be advised of the length of the leave and/or any conditions for 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 in appropriate cases medical information provided by the student, before deciding on an emergency interim leave. An emergency interim 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, use Institute facilities, work on campus, or use student services such as Health and Counseling Services, Center for Diversity, Career Services or the Hixon Writing Center during the leave, unless approved in writing by the dean or designee.

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 or will be permanently separated from the Institute.

Appeal

A decision by the dean to place a student on involuntary leave may be appealed in writing within ten days to the vice president for student affairs (or designee). If the leave is imposed as a sanction resulting from a finding of responsibility under an Institute process any applicable limitations on grounds for appeal will apply.

Withdrawal from the Institute

Formal separation from the Institute is effected by filing a completed undergraduate leave form 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 designee. A student withdrawing from the Institute at any time during the term without filing a formal undergraduate leave form 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 leave 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 leave was granted.

SCHOLASTIC REQUIREMENTS

All undergraduates are required to meet certain scholastic standards as outlined subsequently.

ELIGIBILITY TO BE ENROLLED

All undergraduate students must complete a minimum of 27 units per term with a grade-point average of at least 1.9 in order to be eligible to remain enrolled in classes. Freshmen are not held to the 1.9 GPA requirement during the first two terms when all courses are taken pass/fail. A student may be excused from the 27-unit eligibility requirement if an underload 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. In addition, students must earn a total of 108 units per year; this averages to 36 units per term. The 108 unit requirement may be waived in the case of an approved underload by Add Day, terms away, or having been academically ineligible in one of the past three terms.

When a student is ineligible for the first time, students are to send a reinstatement petition to 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.

When a student becomes ineligible a second time, they 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 signif-
icant 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.

When a student becomes ineligible a third time, they will not be
allowed to continue to enroll at Caltech.

Students who are ineligible to petition may request an exception
to the above. 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. Such requests
require that a reinstatement petition be sent to the Registrar's Office
at least three days prior to the next UASH Committee meeting's
published deadline.

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 subse-
quent 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 require-
ments as well. The approved plan should be submitted to the reg-
istrar 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 designat-

ed 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 27 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.

A Caltech undergraduate degree is based on a four-year residential experience (study abroad included) in which students have the time to explore their academic interested in a deep and rigor-

ous way. Students who are admitted as transfer students or 3/2 students may be granted advanced standing and term credit for academic work accepted in transfer to Caltech. However, transfers and 3/2 students must enroll for a minimum of six terms at Caltech. All other regularly admitted students must enroll for four years (12 terms). Any exceptions to the four year residence requirement must be approved by the dean of undergraduate students and the vice president for student affairs.

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.

Excess of or Fewer Than Normal Units (Overloads and Underloads)

An overload is defined as registration for more than 48 units for an undergraduate. This limit corresponds to five 9-unit classes plus a 3-unit non-academic class (PE, PVA, SA) or four 9-unit classes plus one 12-unit class. Classroom and laboratory courses are to be limited to 45 units for freshmen for the first two terms and the remaining three units should be used for frontier ("pizza") courses, PE, PVA, SA, or research. Students may take up to 51 units (inclusive) but it requires their adviser's approval for such an overload. To take more units than 51, students will need to petition the undergraduate dean, with the expectation that permission will be granted only in exceptional cases. This policy is aimed at having no effect on currently recommended courses of studies in all options, while putting a very high bar for taking 6 full-time classes simultaneously.

A student who wishes to carry an overload in any term must obtain the approval of his or her adviser and the Dean or Associate Dean of Undergraduate Students. Petitions for overloads will not be accepted later than the last day for adding classes in any term.

An underload is registration for fewer than 36 units. Underload petitions for freshmen, sophomores, and juniors must be approved by the adviser and the Dean or Associate Dean of Undergraduate Students. 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 that does not require an overload in any term. Underloads during the first 12 terms will not result in a tuition reduction, only in a reduction in financial aid. After completing 12 terms, tuition will be charged per unit. The dean or disability services coordinator will evaluate exceptions due to medical reasons. For more information about underloads and tuition, see pages 202-203. For more information about impact to aid, see page 220.

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 as well as any supporting class materials required by the option representative, to the representative of the option in which credit is desired. Pending approval by the option representative, credit will be granted when the Allowance of Credit 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 require-ments 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 stand-ing. Credit for comparable work done at other institutions with sim-ilar 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 exec-utive 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 in HSS courses.

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 cours-

es 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 Housing Office by the date specified in the instructions accompanying the contract.

EXPENSE SUMMARY 2019-2020

General:

General deposit...	$100.00[1]
Orientation fee..	$500.00[1]
Tuition..	$52,506.00
	$53,106.00

[1]*This charge is made only once during residence at the Institute.*

Other:

Student fees…..	$2,094.00
Room (contract price....................................	$9,615.00[2]
Board (5 days / week)…...............................	$7,029.00
Books and supplies (est.)…...........................	$1,428.00
Personal expenses (est.)….............................	$2,091.00

[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 12, 2019. Fees are subject to change at the discretion of the Institute.

Tuition for the baccalaureate degree is based on four years (12 terms) of residence regardless of unit load each term or if a student completes graduation requirements a term(s) early. The 12 term residence 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.

Since a Caltech degree is based on a four-year residential requirement, entering students should expect to be in residence and to be billed tuition for a full four years. Any exceptions must be approved by the dean of undergraduate students and the vice

president for student affairs. In addition, aid may not be disbursed to a student to cover full 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 post-withdrawal 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. 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. Also, applicable financial aid will be reduced, in underload situations. For specific information on underload requirements, and special circumstances where an underload may be granted, see page 197. Information regarding financial aid and underloads can be found on page 202, Part Time Enrollments (Underloads.)

For those undergraduate students who are eligible for underloading after completing 12 terms or by approved medical exception (page 197), the tuition will be charged as of Add Day at an AY2019-2020 rate of $486.00 per unit plus $698.00 for student fees per term, with a minimum ten unit charge of $5,558.00 per term.

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. For more information about impact to aid, see page 220, Underloads and Financial Aid.

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 201.

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 disciplinary 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 221.)

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 2018-19	Hard Deadline
Fall Term	November 22, 2019
Winter Term	February 28, 2020
Spring Term	May 22, 2020

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 www.finaid.caltech.edu.

HOW TO APPLY FOR FINANCIAL AID

Application Process for Caltech and Federal Financial Aid for Entering Students (U.S. Citizens and Eligible Noncitizens)
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 www.finaid.caltech.edu.

International Applicants
If you are applying for admission as a freshman for the fall of 2019 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 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, 2019, 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, 2020. Please refer to the complete application instructions provided on the Caltech Financial Aid Office website at 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 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 fed-

eral government based on need and enrollment status. In 2019-20, awards ranged from $650 to $6,195 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 $1,672 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 edu-

cational 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.

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 under-graduate 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, 2019 is currently scheduled to be fixed at 4.53% for undergraduate students.

Undergraduate students:

Enrollment Periods Beginning Between	Interest Rates	
	Subsidized	Unsubsidized
July 1, 2019 - June 30, 2020	4.53%	4.53%
July 1, 2018 - June 30, 2019	5.05%	5.05%
July 1, 2017 - June 30, 2018	4.45%	4.45%
July 1, 2016 - June 30, 2017	3.76%	3.76%
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, 2019 – June 30, 2020	6.08%
July 1, 2018 – June 30, 2019	6.60%
July 1, 2017 – June 30, 2018	6.00%
July 1, 2016 - June 30, 2017	5.31%
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, 2019 – September 30, 2020	1.059%
October 1, 2018 – September 30, 2019	1.062%
October 1, 2017 – September 30, 2018	1.066%
October 1, 2016 – September 30, 2017	1.069%
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
	Unsubsidized
July 1, 2019 – June 30, 2020	7.08%
July 1, 2018 - June 30, 2019	7.60%
July 1, 2017 - June 30, 2018	7.00%
July 1, 2016 - June 30, 2017	6.31%
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, 2019 – September 30, 2020	4.236%
October 1, 2018 – September 30, 2019	4.248%
October 1, 2017 – September 30, 2018	4.264%
October 1, 2016 – September 30, 2017	4.276%
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 Group, P.O. Box 1843, Monticello, KY 42633; (877) 557-2575; fax: (606) 396-4821; visit the website at studentaid.ed.gov/sa/repay-loans/disputes/prepare/contact-ombudsman.

Caltech Loans

Generally, no interest is charged and no repayment of principal is required while a student maintains a continuous course of study at Caltech. 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%. 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.

Please note that students may work no more than 16 hours per week (no more than 12 hours per week as undergraduate teaching assistants). First-year students may not work during fall term. Students can expect to earn at least the City of Pasadena minimum wage of $14.25 per hour. Compensation rates will vary based on the position, a student's skills, and previous work experience.

Additional policies and procedures for teaching assistants, including undergraduates with teaching responsibilities are included in section 4, Teaching Assistantships. (See pages 351–352.)

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 following table to determine which deadline applies to you.

Last Term of Enrollment in Academic Year 2018-19	Hard Deadline
Fall Term	November 22, 2019
Winter Term	February 28, 2020
Spring Term	May 22, 2020

Please go to the work-study page on the Caltech Financial Aid Office website (www.finaid.caltech.edu/TypesofAid/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/AWAY

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 University of Chicago Study Away Program, 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 179.)

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. University of Chicago Study Away Program, 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. University of Chicago Study Away Program participants and 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. 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 (bigfuture.collegeboard.com); and nerdscholar (www.nerdwallet.com/nerdscholar/scholarships/). (For more information on scholarship services, go to www.finaid.org). You may also visit the Financial Aid website at www.finaid.caltech.edu/typesofaid/os/list for a list of outside scholarships.

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 biweek-

ly 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) any time 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 their 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 additional federal, state and institutional financial aid. A student can appeal their unsatisfactory academic progress status and be placed on warning, probation or continued on probation for financial aid purposes.

Satisfactory Academic Progress 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 27 units in the previous term. After the first two terms of study, all undergraduate students must complete a minimum of 27 units with a grade-point average of at least 1.9 in order to remain eligible to register for classes. In addition, students must earn an average of 36 units per term over the past three trailing terms (that is, a minimum of 108 units should be earned after three terms of enrollment each academic year). A student may be excused from the 27-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 rein-

statement 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.

Financial Aid Warning

Students who are found not to be making satisfactory academic progress at the end of an academic term 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 and ineligible for financial aid. Students may appeal this status as outlined in the Caltech Catalog. Ineligible freshmen must petition the UASH Committee for reinstatement if they wish to continue as students and continue to receive financial aid. The dean of students or associate dean may act on a petition if it is the student's first ineligibility.

Undergraduate students, except first- and second-term freshmen, may submit a petition to the UASH Committee for reinstatement, giving any reasons that may exist for their previous unsatisfactory work and stating any new conditions that may lead to better results. Each such petition will be considered on its merits. For the first such ineligibility, the petition may be acted on by the 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. All subsequent reinstatements must be acted upon by the Committee.

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.

Continued on Financial Aid Probation

Students who fail to make satisfactory academic progress after a term on financial aid probation will be ineligible to register and ineligible for federal and state financial aid. These students may appeal this status as outlined above and in the Caltech Catalog.

Students who are reinstated as a result of their appeal/petition for reinstatement will be continued on financial aid probation. These students will be ineligible for federal and state aid. They will continue to be eligible for up to three additional terms of institutional aid but their scholarship eligibility will be reduced in each term the student is continued on financial aid probation.

Financial Aid Suspension

Students who fail to make satisfactory academic progress after being continued on financial aid probation for three additional terms will be ineligible for federal, state *and institutional financial aid*, even if they are subsequently reinstated by the UASH Committee, 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 ▸ 486 x 150% = 729 maximum attempted units.

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)

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. 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 below based on the actual number of units students are enrolled in as of Add Day. Students may NOT receive scholarship assistance for any term in which they are not enrolled at least half-time.

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 or Associate Dean of Undergraduate Students. Underloads for graduating seniors must be approved by the Registrar. (See Caltech Catalog, page 202, for the underload policy.)

The following information summarizes the impact of less than full-time enrollment on financial aid. See page 197 for the separate conditions regarding eligibility to be enrolled less than full-time.

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 to reflect the calculated per-unit tuition and then revise the student's aid (grant eligibility) to reflect the reduction in calculated 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 budget for financial aid purposes to reflect the calculated per-unit tuition and reduce the books and supplies allowance to 1/2 of the standard amount for that term. Federal Pell Grant recipients will have their Pell award reduced according to federal regulations. The Financial Aid Office will revise the student's budget to reflect the per-unit tuition and other reductions in education related costs and then revise the student's aid (grant eligibility) to reflect the reduction in calculated need. Students enrolled 1/2 time can also anticipate an increase in their work-study award for the term.

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 to reflect the calculated per-unit tuition and the books and supplies allowance is reduced to 1/4 of the standard allowance for that term. (As indicated in the Caltech Catalog, the minimum tuition charge is units per term.) The student's aid is revised based on the reduced education related costs. Federal Pell Grant recipients will have their Pell award reduced according to federal regulations. More importantly, the student/family becomes ineligible for scholarship/grant aid awarded by Caltech and for Federal Direct PLUS or Stafford loans for that term. The student will is only eligible for Caltech work-study and loan assistance.

Please note: If the student is enrolled less than half time, the grace period on any student loan (Federal Perkins Loan, Federal Direct Stafford Loan and Caltech and Institute loans) will begin.

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 Administrator. Contact the office Monday through Friday from 8:00am to 5:00pm, with any questions you have.

PRIZES

Advocating Change Together (ACT) Award

Given by the Caltech Y, this award allows students to learn about a global, national, or local issue by immersing themselves with activists working on a cause over the summer and then challenges them to educate others by creating and leading programs designed to raise awareness on campus the following year.

Robert P. Balles Caltech Mathematics Scholars Award

An annual prize is awarded to the mathematics major finishing his or her senior year who has demonstrated the most outstanding performance in mathematics courses completed in the student's time 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 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 their Caltech education. The award is a stipend that will support the student for the summer while they work 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.

Caltech Alumni Spirit Award
Commemorating extraordinary activities by Caltech undergraduate students, graduate students, and postdoctoral scholars who best exemplify the spirit, tradition, and values of Caltech, this award is given only when the Alumni Association finds that exceptional activities have occurred that merit this special recognition.

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.

The Milton & Rosalind Chang Career Exploration Prize
The Milton (PhD '69) and Rosalind Chang Career Exploration Prize encourages and supports recent Caltech graduates who would like to explore careers outside of academia. Graduating students and recent alumni can apply for up to $65,000 in financial support to pursue a bold, compelling, and innovative project to pursue while deliberately taking a break from their current academic or professional path in order to explore other interests, have a diversity of experiences, and develop new skills. Graduating students and alumni interested in fearlessly exploring a new career, volunteer opportunity, or enterprising project are encouraged to apply.

Robert F. Christy Prize for an Outstanding Freshman in Physics
This prize is awarded annually to a freshman who has demonstrated excellence in physics. Established in 2018, this prize honors the memory of Robert F. Christy, former provost and professor of theoretical physics at Caltech.

Robert F. Christy Prize for an Outstanding Senior in Theoretical Physics
This prize is awarded annually to a senior who has demonstrated excellence in theoretical physics through research and/or coursework. Established in 2018, this prize honors the memory of Robert F. Christy, former provost and professor of theoretical physics at Caltech.

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 Award
These two 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 student 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.

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. Awards will be made annually to the engineering students from each option 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 recipients.

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.

Barry M. Goldwater Scholarship

This scholarship program honoring Senator Barry Goldwater was designed to foster and encourage outstanding students to pursue careers in the fields of mathematics, the natural sciences, and engineering. The Goldwater Scholarship is the premier undergraduate award of its type in these fields.

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 was established 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 and carries a cash award of $500.

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.

John H. Hall Memorial Scholarship

This prize recognizes an outstanding undergraduate student in geological and planetary sciences.

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 humanities 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.

Patrick Hummel and Harry Gray Travel Fund

Established as a joint gift from Carla and Paul Hummel, Patrick Hummel, and Shirley and Harry Gray, Caltech's Arnold O. Beckman Professor of Chemistry and founding director of the Beckman Institute, the endowed fund supports undergraduate travel opportunities that promote professional and leadership development and broaden students' perspectives as engaged, responsible citizens of the world.

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.

Dr. James King Jr. Student Diversity Award

The Dr. James King Jr. award recognizes individuals who stand out as strong supporters of diversity within the Caltech student body. The award is named in honor of Dr. King, who was the first African American to receive a Ph.D. from Caltech in chemical physics (at that time it was chemistry and physics, and was the assistant laboratory director at JPL. King had a reputation for mentoring students and encouraged diversity in the Caltech student body.

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.

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.

Gordon McClure Memorial Communications Prize
This prize is awarded to undergraduate students for excellence in written and oral communication skills. Awards will be given in the following fields: English, history, and philosophy.

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.

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 Scholarstauhip
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.

Robert L. Noland Leadership Award
The Robert L. Noland Leadership Award is for upperclass students who exhibit special qualities of leadership. Students who have motivated others to live up to their leadership potential or who have provided excellent "behind the scenes" work in campus activities are those for whom this award is intended. 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.

Dr. Fred Shair Award for Program Diversity

The Dr. Fred Shair Award is given to individuals who stand out as strong supporters of programs that increase the diversity and pluralism in practice at Caltech. Dr. Shair was a member of the chemical engineering faculty, and one of his great accomplishments and contributions to the campus was the creation of the Summer Undergraduate Research Fellowships (SURF) program in 1979. He later included high-achieving students from campuses across the country in an effort to support equity in access to Caltech's research communities.

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.

C.S. Shastry Prize in Physics

The C.S. Shastry Prize in Physics will support a research fellowship for one sophomore undergraduate student conducting research in physics during the summer quarter under the guidance of a Caltech faculty member. The recipient will be nominated by a faculty member based on criteria valued by Professor Shastry: passion for the subject, curiosity about nature, and demonstrated ability. Preferably, the Awardee shall be a student majoring in physics who has completed Caltech's Physics 11 course, and who intends to pursue a research career in physics. The prize is made possible by a gift from Dr. Murali Sharma, a Caltech alumnus who received his Ph.D. in Physics in 1993.

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.

Olga Taussky-Todd Prize
The Olga Taussky-Todd Prize was established by an alumna of Caltech to support women in Mathematics at Caltech. Professor Taussky-Todd (1906-1995) was a pioneer in computer science and algebraic number theory. She was also the first woman to receive a full professorship at Caltech and advised the Institute's first female Ph.D. in Mathematics, Lorraine Foster. The prize will support out-standing undergraduate students majoring in Mathematics through research fellowships and other support to broaden their academic experience.

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 sopho-mores. 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 judges. Each prize is funded by the same source used to sponsor the Eric Temple Bell Prize.

Women Mentoring Women: Candace Rypisi Outstanding Mentor Award
This prize recognizes a woman who has demonstrated a willing-ness to share their knowledge to enhance the professional and per-sonal development of her mentee(s), provided emotional and moral support and encouragement, enhanced or helped facilitate access to career-related information and exposure to various professional resources, opportunities, networks, and other role models, and promoted the mentee's sense of competence and confidence.

Women Mentoring Women: Helen McBride Outsanding Mentee Award
This award recognizes a woman who has demonstrated a sincere desire to succeed as a student, who is committed to her personal development, open and willing to learn from her mentor, and who is receptive to advice and counsel. The recipient will have worked

with her mentor to establish realistic goals, and demonstrated a commitment to carrying them out.

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; 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.

The baccalaureate degree requires four years (12 terms) of residence regardless of unit load each term or the total units earned. The four-year residence 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 2019-20. 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.

233

Courses	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, EE 1, ESE 1, 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] *The biology core requirement can be met by either Bi 1 or Bi 1x. Alternatively, the requirement may be fulfilled by taking both Bi 8 and Bi 9. Nine units must be taken on grades.*

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/EE 24 (9 units), Bi 1x (9 units but only if Bi 1x is not being used to satisfy the biology core requirement), 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 (9 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 (English, history, history and philosophy of science, humanities, music, philosophy, and visual culture) and 36 in the social sciences (anthropology, business economics and management, economics, law, political science, psychology, and 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, cross-listed humanities courses numbered 50 or below in the *Catalog*. These classes introduce students to the basic issues and methods in the disciplines of English, history,

philosophy, and visual culture. 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.

To encourage breadth, students will have to take their two freshman humanities courses in different disciplines, the disciplines being English, history, philosophy, and visual culture.

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 English, history, history and philosophy of science, humanities, music, philosophy, and visual culture. 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 humanities or visual culture. 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 freshman humanities courses and other humanities courses numbered above 90, with the exception of some foreign languages and courses, 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 14 or An 15, Ec 11, PS 12, or Psy 13. 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 here:

Introductory Course	Following Course
An 14 or 15	advanced anthropology
Ec 11	advanced economics or BEM (except BEM 102)
PS 12	advanced political science
Psy 13	advanced psychology

For instance, a student who has taken An 14 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 An/PS 127, Ec 105, Ec 129, Ec 130, Ec 140, PS 99 ab, PS 120, PS 123, or PS 141). 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	SEC 10	one of SEC 11, SEC 12, or SEC 13
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	See Option Requirements	En/Wr 84 or one of SEC 11, SEC 12, or SEC 13
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	-
Bi 1	Principles of Biology	-	-	9
Ch 3 a	Fundamental Techniques of Experimental 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 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/EE 24 (9 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 (9 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, EE 1, ESE 1, 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 6, 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 10.

AEROSPACE MINOR (Ae)

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 (ACM)

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.

ACM 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.

ACM Option Requirements

1. Mathematical Fundamentals: Ma 2; Ma 3; Ma 6 ab or Ma 121 ab; Ma 6 c or CS 21; Ma 108 ab. The analytical tracks of Ma 1 bc are required.
2. Programming Fundamentals: CS 1; ACM 11.
3. Communication Fundamentals: SEC 10; SEC 11, SEC 12, or SEC 13.
4. Core Classes:
   a. Introductory Methods: ACM 95 ab.
   b. Linear Algebra: ACM 104 or ACM 107.
   c. Probability: ACM 116 or CMS 117.
   d. Mathematical Methods: ACM 101 ab.
   e. Numerical Analysis: ACM 106 ab.
5. ACM Electives: In addition to all of the above requirements, three 100+ ACM courses approved by the advisor; up to 9 units of ACM 80 abc or ACM 81 abc can be counted towards this requirement with advisor approval.
6. Sequence: In addition to all of the above requirements, one 27-unit 100+ sequence in science engineering, or social sciences approved by the option representative.
7. Scientific Fundamentals: In addition to all of the above requirements, 18 units selected from Bi 8, Bi 9, Ch 21 abc, Ch 25, Ch 41 abc, Ph 2 abc, or Ph 12 abc.

ACM Typical Course Schedule

| | | *Units per term* | | |
		1st	*2nd*	*3rd*
Second year				
Ma 2	Differential Equations	9	–	–
Ma 3	Intro. to Probability and Statistics	–	9	–

Ma 6 abc Altern. Ma 121 ab + CS 21 (9/18/0)	Intro. to Discrete Mathematics	9	9	9
Science Requirement	See requirements listed above	9	9	-
ACM 11	Intro to Matlab and Mathematica	–	–	6
CS 1	Intro. to Computer Programming	9	–	–
	HSS electives	9	9	9
	Electives (see option requirements 5, 6 above)	–	9	21
	Total	**45**	**45**	**45**

Third Year

Ma 108 abc	Classical Analysis	9	9	-
ACM 95 ab	Intro. Methods of Applied Math	–	12	12
ACM/IDS 104 (or 107)	Appl. Linear Algebra	9	–	–
ACM/EE/IDS 116 (or 117)	Intro. To Probability Models	9	-	-
	HSS electives	9	9	9
	Electives (see option requirements 5, 6 above)	9	12	12
E 10	Technical Seminar Presentation	-	3	-
E 11	Written Tech. Comm. in Engrng and Appl. Sci.	-	-	3
	Total	**45**	**45**	**36**

Fourth Year

ACM/IDS 101 ab	Methods of Appl. Math	12	12	–
ACM 106 ab	Intro. Methods of Comput. Math	12	12	–
ACM/IDS 216	Markov Chains, Discrete Stochastic Processes and Appl. Mathematical Optimization	–	9	–

CMS/ACM/IDS 113	Mathematical Optimization	9	–	–
	HSS elective	9	9	9
	Electives	–	–	27
	Total	**42**	**42**	**36**

APPLIED PHYSICS OPTION (APh)

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 coursework, 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; Plasmaphysics 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.

APh Option Requirements

Note: Items in brackets represent optional replacements.

1. SEC 10 and one of SEC 11, SEC 12, or SEC 13. SEC 11-13 requirement can be satisfied by three units of additional work associated with the senior thesis (APh 78 or APh 79), or by taking Ph 70, En/Wr 84 or Bi/BE 24.
2. Any three of the following: APh/EE 9 b, APh/EE 23, APh/EE 24, Ph 3, Ph 5, Ph 6, or Ph 7.
3. Ph 12 abc, APh/MS 105 ab [Ae/ME 118 or ChE/Ch 165 or Ph 127a; ChE/Ch 164 or Ph 127b], Ph 106 abc, and Ph 125 ab [Ch 125 ab]
4. Ma 2, Ma 3, and ACM 95 ab.
5. Either APh 78 abc or APh 79 abc, or one term of APh 77 and

one term of any of the following: Ph 77, EE 91, Ch 6, Ae/
APh 104 bc, or MS 90. Any substitutions or additions require
prior approval of the option representative.

6. One additional advanced sequence of APh courses num-
    bered over 100, such as: APh 101 abc, APh/MS 105 abc,
    APh 114 abc, APh/Ph 115 and APh/Ph/Ae 116, APh/EE 130,
    131, and 132, APh 156 abc, APh 190 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.

APh Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
ACM 95ab	Intro. Methods of Applied Math.	-	12	12
Ma 2	Differential Equations	9	-	-
Ma 3	Intro. to Probability and Statis-tics	-	9	-
Ph 12abc	Waves, Quantum Mechanics and Statistical Physics	9	9	9
	HSS Electives	9	9	9
	Laboratory Electives[1]	6	6	6
	Other Electives[2]	9	-	9
	Total	**42**	**45**	**45**
Third Year				
APh 105ab	States of Matter	9	9	-
APh 110ab	Topics in Applied Physics	2	2	-
Ph 106abc	Topics in Classical Physics	9	9	9
Ph 125ab	Quantum Mechanics	9	9	-
	HSS Electives	9	9	9
	Other Electives[2]	9	9	27
	Total	**47**	**47**	**45**

Fourth Year

APh 78abc or APh 79abc	Senior Thesis[1] or Senior Thesis, Theoretical[3]	9	9	9
Or APh 77	Laboratory in Applied Physics[3]	-	9	9
	Advanced Electives[2]	9	9	9
	HSS Electives	9	9	9
	Other Electives including APh 100	18	18	18
	Total	**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 APh 79.

ASTROPHYSICS OPTION (Ay)

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.

Undergraduate Information

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.

Ay Option Requirements

1. Ay 20, 21, 101, 102, 30 or one term of Ay 141, Ay 31, 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. Ph 127 a, Ph 136 bc and one of Ph 21, Ph 22, Ph 121 abc are strongly recommended.

4. 27 additional units of science or engineering electives, of which 18 must be outside the Division of Physics, Mathematics and Astronomy. ACM 95 ab is a popular choice. Core classes (see pages 233–238) 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.

Ay 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	9	-	-
Ay 21	Galaxies and Cosmology	-	9	-
Ay 30	Intro. to Modern Research	3	-	-
Ph 3[1] or 5[1]	Physics Laboratory	9	-	-
ACM 95 ab[2]	Intro. Methods of App. Math.	-	12	12
PH 21 OR 22[3]	Computational Tools	-	-	6
	HSS Electives	9	9	18
	Total	**48**	**48**	**45**
Third Year				
Ph 125 abc[4]	Quantum Mechanics	9	9	9
Ph 106 abc	Topics in Classical Physics	9	9	9
Ay 101	The Physics of Stars	9	-	-

Ay 102	Physics of the Interstellar Medium	-	9	-
Ay 104[3]	High Energy Astrophysics	-	-	9
Ph 127 a[3]	Statistical Physics	9	-	-
PH 6[1], 7[1], OR APH 23/24[1]	Physics Laboratory	-	9	9
	Other Electives	-	9	-
	HSS Electives	9	-	9
	Total	**45**	**45**	**45**

Fourth Year

Ay 31	Written Communication	-	-	3
Ay 105[1]	Astronomy Instrumentation Lab	-	-	9
	Ay/Ph Electives	9	9	9
Ay 78	Senior Thesis	9	9	9
Ph 121 3 or Ay 117	Computational Analysis	-	6	-
Ay 141 b3	Research Conference in Astronomy	-	3	-
	Other Electives	18	9	9
	HSS Electives	9	9	9
	Total	**45**	**45**	**48**

[1] *Choose among laboratory classes to satisfy Option Requirement 2.*
[2] *ACM 95 is a popular choice for Option Requirement 4. Other courses may also be used.*
[3] *Strongly recommended courses for Option Requirement 3. Other courses may be substituted.*
[4] *Phys 125c is strongly recommended and can be counted towards Option Requirement 3.*

The sequence Ay 20, 21 constitutes a solid introduction to modern astrophysics, with more advanced courses (Ay 101, 102, plus Ay electives) taken in the junior and senior years. The course schedule above is an example leading to excellent preparation for graduate study, but it is also possible to fulfill the option requirements with a more diverse set of electives across options, and even to take Ay 20, 21 junior year

and Ay 101, 102 senior year. In either scenario, it is desirable for a student to gain as broad a background as possible in related fields of science and engineering. An ability to present one's work is vital to a successful career in any field. The oral communications requirement can be satisfied by presenting during a term of Ay 141, or with Ay 30. 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. Elective credit can be given for no more than 3 terms of Ay 142. Computational skills may be acquired through Ph 20–21, 121, Ay 117, 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 17, APh/EE 23/24, Ay 104, Ay 105, Ay 117, Ay 121–127, 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, 121, 127, 129, 136, 137, 199, 236 (this is not necessarily a complete list).

BIOENGINEERING OPTION (BE)
BE Aims and Scope
The undergraduate bioengineering option provides a foundation for graduate studies and career paths that requires 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, and provide them with opportunities to work in teams through a number of project-oriented courses. Students will receive instruction in scientific communications through Bi/BE 24.

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 adviser 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.

BE Option Requirements

1. BE 1; BE/APh 161; ChE/BE 163; two courses from BE 150, BE 159, and BE/CS/CNS/Bi 191 a.
2. Experimental methods: Bi 1x; one of BE/EE/MedE 189 a or BE 107; one of ChE 130 or BE/CS 196 a. Students are strongly encouraged to enroll in Bi 1x as freshmen; Bi 1x must be completed by the sophomore year. Nine units of BE 98 may be used in place of one of these courses (except Bi 1x) with the approval of the undergraduate option representative to ensure that the student's research project provides comparable experimental laboratory experience. BE 98 units used to satisfy this requirement may not also be counted toward the elective requirement.
3. Biology, chemistry, and physics: two terms out of three from Ph 2 abc (Ch 21 a may be used in place of Ph 2 b and Ch 21 c may be used in place of Ph 2 c); Bi 8; Bi 9; Ch 25; Ch 41 a; Bi/Ch 110. One advanced biology course of at least 9 units selected from Bi/Ch 111, Bi 114, Bi 117, Bi 122, Bi 145 ab, Bi/CNS/NB/Psy 150, BE 150, Bi/BE/CS 183, or approved by the undergraduate option representative.
4. Mathematical and computational methods: ACM 95 ab; Ma 2; Ma 3; one course from ChE 105, CDS 110, or ACM 116; 9 units selected from CS 1, CS 2, CS 3, CS 21, CS 24, and CS 38.
5. 36 units of BE electives. These may include BE 98 (up to 12 units), any BE course numbered 100 or above, any of the BE-approved electives listed below, or any relevant class approved by the student's adviser. Additionally, courses listed in requirements 1-4 that are not used to fulfil those requirements may be counted as electives.
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-Approved Electives

Biology: Bi/Ge 105, Bi/CNS/NB 162, Bi 190.
Biodevices: EE 112, EE 113, EE/MedE 114 ab, APh/EE 9 ab, EE 45, EE 111, EE 151.
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: Ch 41 bc, ChE/Ch 148, ChE/Ch 164, ChE/Ch 165.

BE Typical Course Schedule
(Specific courses are representative and may be substituted per option requirements.)

		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	-
CS 1	Introduction to Computer Programmng	9	-	-
	Freshman Humanities	9	-	9
Bi 1 x	The Great Ideas of Biology: Exploration through Experimentation	-	-	9
BE 1	Frontiers in Bioengineering	-	1	-
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
	Total	**42**	**43**	**45**
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
ChE/BE 163	Introduction to Biomolecular Engineering	12	-	-
BE/CS 196 a	Design & Construction of Programmable Molecular Systems	-	12	-

BE/EE/MedE 189a	Design and Construction of Biodevices	-	-	9
	Menu course	-	-	9
	HSS electives	-	18	9
	Physical education	3	3	-
	Total	**42**	**42**	**48**

Third Year

ACM/EE/IDS 116	Introduction to Probability Models	9	-	-
ACM 95 ab	Introductory Methods of Applied Mathematics	-	12	12
	Advanced BE Electives	9	9	18
Bi/Ch 110	Introduction to Biochem-istry	12	-	-
	Undergraduate Research in Bioengineering	-	6	6
	HSS	9	18	9
	Total	**39**	**45**	**45**

Fourth Year

Bi/BE 24	Scientific Communication for Biological Scientists and Engineers	6	-	-
BE/APh 161	Physical Biology of the Cell	-	12	-
BE/CS/CSN/Bi 191 a	Biomolecular Computation	-	9	-
BE 150	Biological Circuit Design	-	-	9
	Advanced Biology Elective	-	-	9
	Misc. Elective	9	-	9
BE 98	Undergraduate Research	9	9	9
	HSS	9	9	9
	Physical Education	3	-	-
	Total	**36**	**39**	**45**

BIOLOGY OPTION (Bi)

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.

Bi 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/Psy 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, e.g. Ch 25 for Ph2c. 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 Bi 21 with presentation, or three terms of undergraduate thesis (Bi 90 abc).

4. Two courses chosen from Bi/Ch 110, 111, and/or BMB/Bi/Ch 170, 173 or Ch 145.

5. Scientific writing requirement met by taking Bi/BE 24 (six units), or by taking any other writing course such as En/Wr 84 (nine 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 taken for letter grades.
   b. At least two elective courses, of at least nine units each, taken on letter grades.
   c. 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.

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 by passing an exam and then earning a passing grade in Bi/Ch 111 instead. The exam for placing out of Bi 8 is given late in the fall term of freshman year if specifically requested by 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.

- 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. They may be waived if the instructor gives explicit permission.
- Ch 25 is 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 159, BE/APh 161, BE/ChE 163, BMB/Ch 178 and advanced geobiology courses.
- Undergraduates are generally welcome to take 200-level courses with the instructor's permission or strong preparation, unless otherwise indicated.

Bi Typical Course Schedule
(Required courses and representative examples of electives)

		Units per term		
		1st	*2nd*	*3rd*
First Year				
Ma 1 abc	Freshman Mathematics	9	9	9
Ph 1abc	Freshman Physics	9	9	9
Ch 1ab	General Chemistry	6	9	-
Ch 3a	Chemistry Lab	-	6	-
6	Freshman Humanities	9	-	9
CS 1	Introduction to Computer Programming	9	-	-
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Introductory Biology Laboratory	-	-	6
	Total	**42**	**42**	**42**
Second Year				
Ma 2	Differential Equations	9	-	-
Ma 3	Introduction to Probability and Statistics	-	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ch 41abc	Organic Chemistry	9	9	9

	Introductory Social Sciences	9	9	-
	Advanced Humanities	-	-	9
Bi 122	Genetics	9	-	-
Bi 117	Developmental Biology	-	9	-
Bi/CNS/NB/ Psy 150	Introduction to Neuroscience	-	-	10
Bi 160	Molecular Evolution	-	-	9
Bi 22	Undergraduate Research	-	-	10+
	Total	**45**	**45**	**47+**

Third Year

	Advanced Humanities	-	-	9
	Advanced Social Sciences	9	-	9
	Additional HSS	-	-	9
Bi 145 ab	Tissue and OrganPhysiology	9	9	-
Bi/Ch 110	Introduction to Biochemistry	12	-	-
Bi/BE 24	Technical Communication (Fall or Spring)	6	-	6
Bi 118	Morphogenesis Developmental Systems OR	-	9	-
Bi/BE 182	Gene Network Design	-	9	-
Bi/Ch 111	Biochemistry of Gene Expression	-	12	-
BE/APh 161	Physical Biology of the Cell	-	12	-
Bi/CNS/NB 154	Principles of Neuroscience	9	-	-
	OR			
Bi/CNS/NB 164	Tools of Neurobiology	9	-	-
Bi/CNS 158	Vertebrate Evolution	-	-	9
Bi 188 or 190	Human OR Systems Genetics	-	-	6
	Total	**45**	**42**	**48**

	Additional HSS	9	9	9
Bi 114	Immunology	-	9	-
Bi/BE 129	Biology and Treatment of Cancer	-	9	-
Bi 90	Undergraduate Thesis	12+	12+	12+
Bi 192	Introduction to Systems Biology	6	-	-
BE/Bi 103 a	Introduction to Data Analysis in the Biological Sciences	9	-	-
Bi/CNS/NB 195	Mathematics in Biology	9	-	-
Bi/NB/BE 155	Neuropharmacology	-	6	-
Bi 189	The Cell Cycle	-	-	6
Bi/CNS/NB 152	Neural Circuits	-	-	6
Bi 214	Stem Cells	-	-	9
	Total	**45+**	**45+**	**42+**

255

Biology Minor Requirements

The biology 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 biology. Students completing the biology minor requirements will have the phrase "minor in biology" added to their transcripts.

1. *Biology fundamentals.* Bi 8 and Bi 9.
2. *Organic Chemistry fundamentals.* Ch 41a.
3. *Intermediate Biology.* Bi 122; Bi 117; and Bi/CNS/NB/Psy 150.
4. *Advanced Biology.* 18 units of advanced biology electives (100- or 200-level) that are not applied to the above requirements and are not simultaneously used for fulfilling a requirement of the student's major option, approved by their assigned biology advisor or the option representative.

BUSINESS, ECONOMICS, AND MANAGEMENT OPTION (BEM)

The goal of the business, economics, and management (BEM) option is to provide students with the analytical tools to operate successfully in a modern business environment and to prepare students interested in pursuing graduate studies in related fields. The emphasis is on entrepreneurship, finance, and strategy, in

free-market, competitive, and strategic situations. Today's business environment is complex, and therefore required courses in this option are highly analytical. Students often pair the BEM option as a double major with a science or engineering option. The BEM option also serves as a standalone major for students interested in careers in the financial industry, consulting, or entrepreneurial ventures. Expected learning outcomes from completing the BEM option include:

- a strong background in economic theory and econometrics;
- an understanding of the theoretical and practical aspects of finance, risk management, business strategy, and developing new ventures;
- an ability to analyze business problems using qualitative and quantitative methods;
- an ability to analyze financial and business data;
- an ability to write and communicate effectively; and
- an understanding of the broader impacts of business and management on society in general.

Note: **The official source on requirements for graduation is the Caltech catalog from the year in which a student began studies at Caltech. Please see the catalog online, from this and previous years, for information regarding the applicable option requirements.**

BEM 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, and PS/Ec 172.
2. BEM 102 and BEM 103.
3. Three courses out of BEM 104, BEM 105, BEM 110, or BEM 117.
4. 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.
5. 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), ACM 113, ACM/EE 116, An/PS 127, BEM/Ec 150, CS/SS/Ec 149, Ec/ACM/CS 112, Ec 105, 121 ab, 129, 130, 131, 135, Ec/PS 160 abc, Ge/ESE 118, Ma 112a , Ma/ACM 144ab, PS 12, and Psy 13. No more than one from these three: CMS/CS/CNS/EE/IDS 155, CS/CNS/EE 156a and IDS/ACM/CS 157. Other courses with permission of BEM option representative.
6. 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).
7. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

BEM 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 toAccounting	-	-	9
BEM 103	Introduction to Finance	9	-	-
PS/Ec 172	Game Theory	-	9	-
	Electives [1]	18	27	27
		45	45	45
Third Year				
BEM 104	Investments	-	9	-
BEM 105	Options	9	-	-
Ec 122	Econometrics	9	-	-
	Electives [1]	27	37	45
	Total	**48**	**45**	**45**
Fourth Year				
En/Wr 84	(or 3 unit course in oral communications and a scientific writing require-ment course	-	-	9
Ec 105	Firms, Competition, and Industrial Organization	9	-	-
BEM110	Venture Capital	-	9	-

257

Electives		36	36	36
Total	**45**	**45**	**45**

CHEMICAL ENGINEERING OPTION (ChE)

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. In addition, the chemical engineer may use computational methods – from the atomic, molecular, and continuum levels to the chemical process, plant, and enterprise levels – to improve understanding; design experiments & interpret data; predict key attributes; and develop new or improve existing materials, methods, and processes.

Key educational objectives of our chemical engineering curriculum are to prepare students for professional practice at the forefront of

258

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), as well as general chemistry laboratory (Ch3a [or Ch 3x]).

Sophomores take ordinary differential equations (Ma 2), wave physics (Ph 2a), and organic chemistry laboratory (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 63 ab). The third-year applied and computational mathematics course (ACM 95 ab) 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 five tracks (biomolecular, environmental, materials, process systems or computational), 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.

ChE 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/Wr 84), ACM 95 ab, ChE 101, ChE 103 abc, ChE 105, ChE 126, and one of Ec 111, BEM 102, or BEM 1031.

2. Completion of a track (biomolecular, environmental, process systems, materials or computational), each consisting of at least 72 units of science or 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 c], and additional units of bioengineering or biochemical engineering electives or approved related courses.[3,4]

b. Environmental track: two of the core ESE courses [ESE 101, 102, and 103], [ChE 128 or ChE 90 c], and additional units of ESE electives or approved related courses.[3,4]

c. Process systems track: ChE 118, ChE 120, [ChE 128 or ChE 90 c], and additional units of engineering electives, courses from the other tracks, or approved related courses.

d. Materials track: [ChE 128 or ChE 90 c]; one course on materials synthesis or processing selected from [Ch/ChE 1472, ChE 1152, or MS 133]; at least one course on the physical basis of structure and properties selected from [Ch 120, ChE/Ch 1482, MS 115, MS/APh 122, MS 131, or MS 132]; and additional units of chemical engineering, materials science, or applied physics elective courses selected from ChE 118, ChE 120, ChE/Ch 1552, ChE/Ch 164, ChE/Ch 165, APh 109, APh 114 ab, any MS course, or approved related courses.[3,4]

e. Computational track: ACM/IDS 104, ChE 141, at least one course sequence from [Ch 121 ab; BE 163 & BE 191 a; ESE 101 & ESE 136; Ae 232 ab; or ChE 90 abc], and additional units from ChE 142 or approved courses in IDS, ACM, CS or related options.[3]

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 (except when courses are only available P/F)

4. Passing grades must be earned in a total of 486 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.

[3] No more than 18 units of [ChE 90ab or ChE 80] may count as track electives.

[4] ChE 118 and/or ChE 120 may be elected provided the design project undertaken contains a significant component relevant to the track.

ChE 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 15	Introduction to Chemical Engineering Computation	9	-	-

Course	Title			
Ch/ChE 9	Chemical Synthesis and Characterization	-	-	9
	for Chemical Engineering			
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
PE	Physical Education	-	3	-
	HSS electives	9	-	-
	Total	**45**	**42**	**39**

Third Year

Course	Title			
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 electives1	9	9	9
Ec 11, BEM 102, or BEM 103		9	-	-
	HSS electives	9	18	18
	Total	**39**	**45**	**45**

Fourth Year

Course	Title			
ChE 126	Chemical Engineering Lab	9	-	-
	ChE, Ch, track courses, and electives1	18	18	9
Ch 21 abc2	Physical Chemistry	9	9	9
	HSS electives	9	9	18
	Total	**45**	**36**	**36**

[1] See option requirements.

[2] Ch 24 can be substituted for Ch 21 b.

CHEMISTRY OPTION AND MINOR (Ch)

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. Ch 1 ab must be passed to satisfy the Institute chemistry requirement. 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. The one-term required laboratory course (Ch 3 a or 3 x) presents basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. Qualified students, with the consent of the instructor and the option representative, 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, and Ch 41 ab.

Ch 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.

Ch 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.

Ch Option Requirements

1. Ch 14, Ch 21ab, Ch 21 c or Ch 25, Ch 41abc, Ch 90, Ma 2, and Ph 2a. Ma 3 is recommended but not required. Students may make the following substitutions: For Ch14 (Ch/ESE175);

for Ch 21a (Ph 2b, Ph 12b, Ch 125a or Ph 125a); for Ch 21b (Ch 126); for Ch 21c (Ph 2c, Ph 12c, ChE/Ch 164 or Ph 127a). 100-level courses used in substitution for these option requirements may not also be counted towards the five terms of advanced electives.

2. A minimum of five terms of laboratory work chosen from Ch 4ab, Ch 5ab, Ch 6ab, Ch 7, and Ch 15. One non-chemistry laboratory course may be used, chosen from MS 90, Ph 6 and Ph 7. One term of research, either 10 c (if taken freshman or sophomore year) or one term of Ch 82 (Senior Thesis), if taken for grades as the third and final term, may count for one of the five electives.

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. Students may petition to substitute up to but no more than one 100-level elective from another option, if the substituted course has substantial chemistry content. Ch 101 cannot be used to meet the five term requirement but can be used to meet the 45 unit requirement for advanced electives.

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.

The chemistry option strongly encourages students to engage in academic year research, and up to 27 units each of Ch 80 and Ch 82 can count toward the 486-unit requirement.

Ch 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	-	9	-
	Electives	18-21	18-27	18-21
	Total	**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 or Ch 21 ab, Ch 25	Physical Chemistry	9	9	9
Ch 90	Oral Presentation	-	3	-
Ch/ChE 91	Scientific Writing	-	-	3
	Electives	17-29	21-36	33-36
	Total	**45–48**	**45–48**	**45–48**

Fourth Year

Ch 6 a	Physical and Biophys. Chemistry Lab	-	9	-
or Ch 6 b		-	-	9
or Ch 7	Advanced Experim. Methods in Bioorganic Chemistry	-	-	9
	Electives	45–48	35–48	26–48
	Total	**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 laboratory, Ch elective(s), Ch 80, Ch 90, Ch/ChE 91, HSS elective	Ch 6 a or 6 b, or Ch 15 Ch elec-tives, 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 15, 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 15, 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 ab, Ch 25 (or Ch 21 bc), Ch 80 (or Bi 22), Ch 90, Ch/ChE 91, Bi/Ch 110, Bi/Ch 111, Bi 10	Ch 6 a or 6 b, Ch 15, Ch (Bi) electives, Ch 80 (or Bi 22), HSS elective

Ch Minor Requirements

The chemistry 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 chemistry. Students completing the chemistry minor requirements will have the phrase "minor in chemistry" added to their transcripts.

1. 18 units of organic chemistry, taken from Ch 41 abc.
2. 18 units of physical chemistry, taken from Ch 21 abc (or substitute as specified for the major).
3. 27 units of advanced chemistry electives numbered Ch 102 or above, approved by their designated chemistry adviser or the option representative.
4. 9 or more units of a chemistry laboratory course from Ch4ab, Ch 5 ab, Ch 6 ab, Ch7 or Ch15. No substitutions are allowed.

All courses to be applied to fulfill the minor requirements must be taken for grades. Courses taken as part of the chemistry 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. Courses that are used to satisfy the Chemistry minor requirements cannot be used to satisfy course requirements in another major.

COMPUTATION AND NEURAL SYSTEMS OPTION (CNS)

Aims and Scope

The undergraduate CNS option provides a foundation in math, physics, biology and computer science to prepare students for interdisciplinary graduate studies in neuroscience and career paths that involve computational applications inspired by properties of biological systems, such as artificial intelligence and computer vision. By graduation, students will have acquired knowledge in neurobiology, computation principles across different systems, methods used in modern neuroscience research, as well as the ability to critically evaluate and understand neuroscience literature, and be able to work in a team and communicate effectively.

To accomplish these goals, students are expected to complete a series of math and physics courses to establish solid quantitative skills. Then, they are expected to take two groups of courses, of which one has a biology focus, while the other has a CS focus. Through these courses, students are exposed to different sub-disciplines of neuroscience while also acquiring the quantitative skills needed in graduate research and industry jobs. Students will receive instruction in scientific communications through SEC 10 and SEC 11, SEC 12, SEC 13, or Bi/BE 24.

Undergraduate research is encouraged both during the academic year and through participation in summer research programs.

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.

267

CNS Option Requirements

1. Fulfillment of extended core requirements in Differential Equations (Ma 2 or equivalent); Probability and Statistics (Ma 3, Ge/ESE 118 or equivalent); Waves (Ph 2a, Ph 12a or equivalent), Thermodynamics and Statistical Mechanics (Ph 2c, Ph 12c or equivalent).
2. Demonstration of competency in computer programming or computer science by taking CS 1, CS 2, and one of BE 103 and CS 3 or by taking an approved alternative course, or by passing a placement exam administered by the computer science option.
3. Bi/CNS 162 and 9 units of laboratory courses taken from the following list: CS/CNS 171, CS/CNS 174, EE 45, EE/CS 53, EE 90, EE 91 ab, ME 72 ab, ME 50ab, BE 107, BE/EE/MedE 189 a, BE/CS 196a, Bi/BE 227, Bi/CNS/BE/NB 230.
4. ACM 95 ab, or Ma 108 abc, or Ma 109 abc.

5. SEC 10 and SEC 11, SEC 12, or SEC 13; or Bi/BE 24.
6. Bi 8, Bi 9, Bi/CNS/NB 150, Bi/CNS/ NB 157, Bi/CNS/NB 164.
7. Choose five from the following list: EE 111, CS/CNS/EE 156 ab, CS/CNS/EE 155, CS 159, CNS/Bi/EE/CS/NB 186, CNS/Bi/Ph/CS/NB 187, BE/CS/CNS/Bi 191a, BE 150, IDS/ACM/CS 157.
8. 45 units of electives chosen from either advanced EAS courses or advanced science courses offered by BBE, CCE, GPS, or PMA divisions.

CNS Typical Course Schedule

		Units per term		
		1st	2nd	3rd
First Year				
CS 1	Introduction to Computer Programming	9	-	-
CS 2	Introduction to Programming Methods	-	9	-
	Freshman Humanities	9	9	9
	Freshman Core	27	27	27
	Total	**45**	**45**	**42**
Second Year				
Ph 2 ac	Waves, Statistical Mechanics	9	-	9
Ma 2, Ma 3	Sophomore Mathematics	9	-	-
ACM 95 ab	Intro. Methods of Applied Math	-	12	12
EE 111	Signals and systems	9	-	-
Bi 8, 9	Molecular, Cell Biology	-	9	9
Bi 150	Introduction to Neuroscience	-	-	10
	HSS Electives	9	9	9
	Electives	9	9	-
	Total	**48**	**39**	**49**
Third Year				
BE 103	Data Analysis in Biological Sciences	12	-	-

Bi 164	Tools in Neurobiology	9	-	-
CS 156 a	Learning Systems	-	-	9
Bi 162	Cellular and Systems Neuroscience Lab	-	12	-
BE/CS 191 a	Comparative Nervous Systems	-	-	9
	Engineering Lab	-	-	9
	HSS Electives	9	9	9
	Electives	9	18	18
	Total	**45**	**48**	**45**

Fourth Year

CNS 187	Neural Computation	9	-	-
CNS 186	Vision: From Computational Theory to Neuronal Mechanisms	-	12	-
CS 159	Advanced Topic in Machine Learning	-	-	9
SEC 10, SEC 11-13	Scientific Communication	3	-	3
	HSS Electives	9	9	9
	Electives	18	18	18
	Total	**39**	**39**	**39**

COMPUTER SCIENCE OPTION AND MINOR (CS)

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 http://cms.caltech.edu/academics/ugrad_cs may be helpful for this purpose).

Any student in the computer science 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 work in the option.

CS Double Majors

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 72 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.

CS 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/IDS 121, CS 122, CS 123.
      ii. A graphics project class (CS 174, CS 176, or CS ACM 177 b) as well as two other CS 17x courses.
      iii. sLearning & Vision: At least three courses chosen from EE/CNS/CS 148, CMS/CS/CNS/EE/IDS 155, CS/CNS/EE 156 ab, IDS/ACM/CS 157, ACM/CS/EE IDS 158, CS/CNS/EE/IDS 159, CNS/Bi/EE/CS/NB 186, CNS/Bi/Ph/CS/NB 187, Ec/ACM/CS 112, including at least one of 148, 156 b, 159, or 186.
      iv. Networking & Distributed Systems: CS 141, CS/EE 145, or EE/CS 147 combined with two courses chosen from CS/IDS 142, CS/EE/IDS 143, and CMS/CS/EE/IDS 144.
      v. Quantum & Molecular Computing: At least three courses chosen from BE/CS/CNS/Bi 191 ab, BE/CS 196 ab, ChE 130, Ph/CS 219 abc.
      vi. Robotics: At least three courses chosen from ME 115 ab, ME/CS/EE 133 B, ME/CS/EE 134, EE/CNS/CS 148, CNS/Bi/EE/CS/NB 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/IDS 139, CS/IDS 142, CS/EE/IDS 143, CS/IDS 150 a, or CS 151.

5. Mathematical fundamentals. Ma 2/102; Ma 3/103; Ma/CS 6a or Ma 121a.
6. Communication fundamentals. SEC 10; SEC 11, SEC 12, or SEC 13.
7. Scientific core electives. 18 units selected from the following courses: Bi 8, Bi 9, Ch 21 abc, Ch 24, Ch 25, Ch 41 abc, Ph 2 abc, or Ph 12 abc. Advanced 100+ courses in Ay, Bi, BE, Ch, CNS, Ge, MedE, or Ph with strong scientific component can be used to satisfy this requirement with approval from the option representative.
8. Breadth. In addition to all of the above requirements, 36 units in Ma, ACM, or CS; 18 units in EAS or Ma; and 9 units not labeled PE, PVA or SA.

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.

271

CS 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 3	Intro. to Software Design	-	-	9
CS 38	Introduction to Algorithms	-	-	9
	HSS electives	9	-	18
	Other electives	-	-	9
	Total	**45**	**45**	**45**

Third Year

	CS courses		-	9	9
CS 24	Intro to Computing Systems		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	-
		Total	**45**	**45**	**39**

Fourth Year

	CS courses		9	9	-
	HSS electives		9	9	9
	EAS/Ma courses		9	9	9
	Other electives		18	9	18
		Total	**45**	**36**	**36**

[1] *Commonly taken during the freshman year.*

CS 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.

CS Minor Requirements

Computer Science Minor

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

- Complete CDS 110 or CDS 131 and CDS 231 or CDS 232
- Complete nine additional units in CDS courses, chosen from CDS 110, CDS 112, CDS 131, CDS 141, CDS 232, CDS 233, CDS 242, CDS 243, CDS 244.
- 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 232 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 (Ec)

The economics option provides students with an understanding of the basic principles underlying the functioning of economic institutions. It offers a modern quantitative approach seldom available at the undergraduate level. The emphasis on economic principles and modern methodology provides students with an excellent preparation for graduate study in economics, as well as for professional work in the fields of business, law, economics, and government.

The option is sufficiently flexible so 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.

Expected learning outcomes from completing the economics option include:

- a proficiency in applying economic models to understand economic institutions;
- a proficiency in analyzing field and experimental data to prove causal relationships between economic variables, to test economic theories, and to predict economic outcomes;
- an understanding of the causes of regional and global long-term economic growth as well as the causes and consequences of economic crises throughout history;
- an understanding of the role of market prices in allocating resources and affecting the distribution of wealth;
- an appreciation of strategic behavior and asymmetric information in economic and social interactions; and
- an appreciation of the role of technological change and politics in shaping economic policies.

Note: **The official source on requirements for graduation is the Caltech catalog from the year in which a student began studies at Caltech. Please see the catalog online, from this and previous years, for information regarding the applicable option requirements.**

Ec 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 or Ec 135.
5. Macroeconomics and growth: one of Ec/SS 129, 130, or Ec 140.
6. Ma 3.
7. 45 additional units of advanced economics and social sci-

ence 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/EE/IDS 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.

Ec 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
	Total	**36**	**36**	**45**
Third Year				
Ec 105	Firms, Competition, and Industrial Organization	9	-	-
Ec 121ab	Theory of Value	9	9	-
PS/Ec 172	Game Theory	-	9	-
Ec 122	Econometrics	9	-	-

Electives [1]		18	27	45
	Total	**45**	**45**	**45**

Fourth Year

En/Wr 84 (or 3 unit course in oral communication and a scientific writing requirement course)		-	-	9
Electives [1]		45	45	36
	Total	**45**	**45**	**45**

[1] *See option requirements 5 and 7.*

ELECTRICAL ENGINEERING OPTION (EE)

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, robotics, 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 is also intended 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 2 as a freshman-year elective. The formal study of electrical engineering begins in the sophomore year with courses such as, Deterministic Analysis of Systems and Circuits, EE 44; Introduction to Digital Logic and Embedded Systems EE/CS 10ab; 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. The junior year

features the fundamentals of signals and systems and digital signal processing, EE 111; random variables and stochastic processes, ACM/EE/IDS 116; 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, and CS/EE/ME 75 c. In addition, the student throughout his/her studies and 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 281.)

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.

EE 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 academic 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.

EE Option Requirements

1. Ma 2, Ma 3, Ph 2 abc. Ph 12 abc can replace Ph 2 abc.
2. APh 109 or a sequence consisting of APh/EE 23 and APh/EE 24
3. EE 2, SEC 10, one of SEC 11-13, EE/CS 10ab, EE 40, 44, 45, 90, 111, 151, EE/CS/IDS 160 and ACM/EE/IDS 116.
4. ACM 95 ab.
5. EE 113 or CDS 110.
6. One term of EE 91.
7. EE 80 abc, or a sequence consisting of CS/EE/IDS 143, CS/EE 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 119 c, and CS/EE/ME 75 c (note that CS/EE/ME 75 ab does not satisfy this requirement).

8. In addition to the above courses, 45 units selected from any EE course numbered over 100, or any cross-listed courses numbered over 100 that include EE in the listing. These units must also include at least one course taken for two quarters (an ab sequence). Included in these units must be at least one of EE 112, EE/Ma/CS 126a, or EE/Ma/CS/IDS 127.

9. Passing grades must be earned in a total of 486 units, including courses listed above. Courses used to satisfy requirements 1 through 8 must be taken for grades, unless they are only offered pass/fail.

EE 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	Physics of Electrical Engineering	-	-	9
EE 44	Deterministic Analysis of Systems and Circuits	12	-	-
EE 45	Electronics Systems and Laboratory	-	12	-
EE 113	Feedback and Control Systems	-	-	9
EE/CS 10 ab	Introduction to Digital Logic and Embedded Systems	-	6	6
	Electives	9	-	-
	Total	**48**	**45**	**42**
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	Physics of Electrical Engineering	-	-	9
EE 44	Deterministic Analysis of Systems and Circuits	12	-	-
EE 45	Electronics Systems and Laboratory	-	12	-
EE 113	Feedback and Control Circuits	-	-	9
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
	Electives	9	-	-
	Total	**48**	**51**	**48**

Third Year – Schedule 1

SEC 10	Technical Seminar Presentations	3	-	-
one of SEC 11-13	Written 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/CS/IDS 160	Fundamentals of Information Transmission and Storage	-	9	-
EE 90	Analog Electronics Project Lab	-	-	9
ACM/EE/IDS 116	Introduction to Probability Models	9	-	-
	Electives	9	9	9
	Total	**39**	**42**	**48**

Third Year – Schedule 2

SEC 10	Technical Seminar Presentation	3	-	-

one of SEC 11-13	Written Communication	-	3	-
EE/CS 10 ab	Introduction to Digital Logic and Embedded Systems	-	6	6
	HSS electives	9	9	9
EE 151	Electromagnetic Engineering	-	-	9
EE 111	Signals, Systems, and Transforms	9	-	-
EE/CS/IDS 160	Fundamentals of Information Transmission and Storage	-	9	-
EE 90	Analog Electronics Project Lab	-	-	9
ACM/EE/IDS 116	Introduction to Probability Models	9	-	-
	Electives	9	18	9
	Total	**39**	**45**	**42**

Fourth Year (for project)

	HSS electives[1]	9	9	9
EE 91 ab[2]	Experimental Projects in Electronic Circuits	**9**	-	-
	EE electives	9	9	9
	Electives	9	18	18
		36	36	36

Fourth Year (for thesis)

	HSS electives[1]	9	9	9
EE 91 ab[2]	Experimental Projects in Electronic Circuits	9	-	-
EE 80	Senior Thesis	9	9	9
	EE electives	9	9	9
	Electives	3	9	9
	Total	**39**	**36**	**36**

[1] See Institute requirements for specific rules regarding humanities and social sciences.

[2] See option requirements 6 and 7.

EE Suggested Electives

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 inter-disciplinary 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, EE/MedE 114, BE 141, EE/BE/MedE 185, CNS/Bi/EE/CS/NB 186, BE/EE/MedE 189 ab.

Communications and Signal Processing
Second Year: Selected from APh 17 abc, APh/EE 23, APh/EE 24, Third and Fourth Year: EE 112, EE/Ma/CS 126 ab, EE/Ma/CS/IDS 127 ab, EE 128 ab, 164, EE/CS/IDS 160, 167, EE/CS 161, 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 110abc, 153, EE/CS 119 ab, EE/CS/MedE 125, and selections from EE 112, CS 185 abc, EE/APh 180, EE/CS 119, EE/CS/IDS 160, EE 128 ab.

Microwave and Radio Engineering
Second Year: APh/EE 23, APh/EE 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/EE 23, APh/EE 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/MedE 185, EE/MedE 187.

Robotics
ME/CS/EE 134 and two more courses from the following list: ME/CS/EE 133 ab, EE/CNS/CS 148, CNS/Bi/EE/CS/NB 186, CDS 131, CMS/CS/CNS/EE/IDS 155.

ENGINEERING AND APPLIED SCIENCE OPTION (EAS)

The engineering and applied science (EAS) option offers students the opportunity for study in a wide variety of challenging areas of science and technology by allowing each student to design a customized course of study that has breadth, depth, and rigor similar to the options 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.

EAS Option Requirements

Students who have elected the EAS option must either choose one of the approved areas of concentration (see item 7 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 representative.

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 (Ma 3, Ge/ ESE 118 or equivalent); Waves (Ph2a, Ph12a or equivalent), Quantum Mechanics (Ph 2b, Ph 12b, Ch 21a or

equivalent); Thermodynamics and Statistical Mechanics (Ph 2c, Ph 12c, ChE 63, ME 11, Ch 21c 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, CE, CS, CDS, EE, ESE, MS, or ME;
and
b. 27 additional units of either advanced EAS courses or advanced science courses offered by the BBE, 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 180, CS/CNS 171,174, EE 45, 53, EE 90, EE 91 ab, MS 90, MS 125, ME 72 ab, ME 50 ab, ME 90 bc; and
b. 9 units of additional laboratory courses either from the list in 3a 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. SEC 10 or equivalent; one of SEC 11, SEC 12, or SEC 13 or equivalent.

7. Courses used to satisfy requirements 1–5 above must also satisfy a depth requirement, which must be met by a customized schedule of requirements that is rigorous, 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. The student must submit a written proposal justifying their course selections, and obtain the approval of, the EAS optio representative by the end of the third term of the sophomore year.

8. At least 117 units of EAS courses not including those used to satisfy requirements 4, 5, and 6 above.

9. The customized schedule of requirements described in 7 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.

ENGLISH OPTION AND MINOR (En)

The option in english provides students with a broad and intensive education in the rich traditions of literature in english from the middle ages to the present day, with a particular emphasis on british and american writing. The english faculty expects undergraduate option students to become familiar with a range of literary forms, genres, and styles of expression; to understand how authors and texts can be shaped by historical contexts; to appreciate differences in literary expression across time periods and national traditions; to develop critical reading skills through analysis and interpretation of literary texts; and to become effective writers in matters of style, organization, and interpretive argument.

During the senior year, and typically in the first two terms, English option students enroll in En 99 ab (Senior Tutorial for English Majors) with a faculty member chosen by mutual agreement. The Senior Tutorial introduces students to advanced methods in literary research and analysis and provides an important means for assessing the progress of English option students in the rigorous study of literary texts and contexts. Students research, write, and revise a 25-30 page paper on a topic in British or American literature; En 99 a is primarily a research term, and En 99 b is primarily a writing term. Both terms involve regular tutorial consultation with the faculty instructor. English option students should begin considering a senior thesis topic in the third term of their junior year in consultation with the option representative or option adviser.

In addition to the Senior Tutorial, the English option requires nine courses, which must include at least one course in each of the following areas: British literature, American literature, and literature before 1850. All English option students are assigned an adviser who will help select courses best suited to their needs and interests, including where appropriate a limited number of courses in related fields such as history, visual culture, and literature other than British and American. Students should consult their option adviser in advance of registration for each term. All courses counted toward the option must be taken for grades except for a freshman humanities course in English when taken in the first two quarters of the freshman year.

Most students pursue English as a second option. The emphasis on writing and on critical reading helps students develop communication skills that can enhance their careers as scientists, engineers, and medical professionals. The English option also provides excellent preparation for those seeking careers in law, business, and administration, and in any field that involves extensive communication.

En 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 103, 110, 113, 118, 121, 122, 125, 127, 129, 188, 189, 190, and En/H 193, 197). Courses cannot be counted twice in meeting these distribution requirements. Up to nine units of freshman humanities in English (courses cross-listed Hum/En numbered 50 or below) 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 freshman humanities in English (courses cross-listed Hum/En numbered 50 or below) may be substitute 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 (ESE)

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.

GEOLOGICAL AND PLANETARY SCIENCES (GPS)
(Geology, Geobiology, Geochemistry, Geophysics, Planetary Science)

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.

GPS 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.

GPS Option Requirements

Geology Option Requirements

1. Ge 11 ab, Ge/Ay 11 c or Ge 11 d[1], and any writing class and oral presentation class that satisfies the Institute scientific requirements[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 (selected in consultation with adviser and approved by the option representative).

[1] *No class may be used to simultaneously satisfy more than one of these requirements.*

[2] *For example, SEC 10 and one of SEC 11, SEC 12, SEC 13, or can be satisfied by En/Wr 84.*

[3] *If Ge 120b is not offered, a suitable 3-5 week field camp may be substituted.*

GPS Typical Course Schedules

		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.	-	-	9
	HSS electives	9	9	9
	Total	**36**	**36**	**36**

Summer

Ge 120 b	Field Geology Camp	-	-	15

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
	Total	**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
SEC 10	Oral Presentation	-	-	3
	Total	**18**	**27**	**24**

Geobiology Option Requirements

1. Ge 11 abc.
2. Bi 8, 9.
3. Ma 2 and one course in statistics and data analysis (Ma 3, Bi/CNS/NB 195, Ge/Ay 117, or Ge/ESE 118).
4. Two quarters of sophomore-level physics (Ph2a, b, c, or 12a, b, or c).
5. Ch 41 abc and Bi/Ch 110.
6. Any writing class that satisfies the Institute scientific writing requirement [1]; or Bi 24.

7. At least 9 units of laboratory instruction from: Bi 10, Ch 7, Ch 8, Ch 15, Ge 116, or Ge 120ab[2].
8. Any six courses from the geobiology core: Bi 117, Bi 122, ESE/Bi 166, ESE/ Bi 168, Ge/ESE/Bi 178, Ge 112, 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[3].

[1]For example, one of SEC 11, SEC 12, SEC 13 or En/Wr 84; with the approval of their adviser, students may also petition to do independent writing with a faculty member under Ge 40.

[2]May also be satisfied by units from other courses that have a laboratory component, or substitute thesis research or independent laboratory research, all with approval of option representative.

[3]May include any courses listed above that are not being used to fulfill a separate requirement.

		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 abc	Intro. to Earth and Planetary Sci.	9	9	9
Bi/BE 24	Writing and oral presentation	-	-	6
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Cell Biology Laboratory	-	-	6
	HSS electives	9	9	9
	Total	**36**	**36**	**48**
Third Year				
Bi/Ch 110	Intro. to Biochemistry	12	-	-
Ge 124 ab	Paleomagnetism	-	-	15
	Scientific Writing	-	3	-
Ch 41 abc	Organic Chemistry	9	9	9
	HSS electives	9	9	9
	Geobiology electives	-	9	-
	Total	**30**	**30**	**42**

Fourth Year

ESE/Bi 166	Microbial Physiology	9	-	-
ESE/Bi 168	Microbial Metabolic Diversity	-	9	-
Ge/ESE/Bi 178	Microbial Ecology	-	-	9
Ge 143	Organic Geochemistry	-	-	9
Bi 122	Genetics	9	-	-
Ge 112	Sedimentology and Stratig-raphy	12	-	-
Ge 116	Analytical Laboratory Tech-niques	-	9	-
	HSS electives	9	9	9
	Geobiology electives	-	-	9
	Total	**39**	**27**	**36**

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 sopho-more-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, Ge/ESE 140 c, Ch 21 a, Ch 41 a, ESE/Ge/Ch 171, Ge/ESE 143, 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 5 a, b, Ch 6 a, b, Ch 7, Ch 8, Ch/ChE 9, Ch 14, Ch 15, Ch 21 b, c, Ch 41 b, c, Ch 102.
7. *ChE electives:* ChE 63 a, b. *ESE electives:* 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, Ge 120 a, b, Ge/Ch 127, Ge/Ch 128, Ge/Ay 132, Ge 191, Ge 212, Ge 214, Ge 215.
   APh electives: APh 17 a, b, c.
   MS electives: MS 105, MS 115, MS 125, MS 131, MS 133, MS 142, MS/ME 161

[1] No class may be used to simultaneously satisfy more than one of these require-ments.

[2] For example, SEC 11, SEC 12, SEC 13, 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 (GeCh option)	-	-	6
	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
	Total	**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
	Total	**18**	**18**	**18**

Geophysics Option Requirements

1. Ge 11 a, Ge 11 b or Ge 11/Ay c, SEC 10 and a science writing course.[1]
2. Ge 111 ab, Ge 11 d
3. Ph 2 a or 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 11 and 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, SEC 11, SEC 12, SEC 13, 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
SEC 10	Oral Presentation	-	-	3
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2 & Ma 3	Sophomore Mathematics	9	9	-
	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	-
	Total	**18**	**45**	**39**
Fourth Year				
	Geophysics electives	18	18	9
	HSS electives	9	9	9
	Total	**27**	**27**	**18**

Planetary Science Option Requirements

1. Ma 2 and one of Ma 3, Ge/Ay 117, or Ge/ESE 118.
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, 3 units of oral presentation (SEC 10 or 3 units of Ge 109, including an oral presentation at planetary sciences seminar), 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, Ge/Ay 137, Ge/Ay 159, ESE 101-103, Ge/ESE 150, Ge 151, Ge/EE/ESE 157 c, ESE 130, Ge/ESE 139.

[1] For example, SEC 11, SEC 12, SEC 13, 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
Ph 2 abc	Sophomore Physics	9	9	9
Ma 2, 3	Sophomore Mathematics	9	9	-
	HSS electives	9	9	9
	Total	**36**	**36**	**30**
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
	Total	**27**	**39**	**39**
Fourth Year				
	HSS electives	9	9	9
	Planetary science	9	9	9

Additional science and engineering	9	9	9
Total	**27**	**27**	**27**

GPS Division Minor Requirements

The minors in the GPS Division are intended for non-GPS undergraduates to supplement a major degree with knowledge of earth and planetary science. Students may complete a minor in either Geobiology, Geochemistry, Geology, Geophysics, Planetary Sciences or a general GPS minor, and will have the phrase "minor in [the appropriate option]" added to their transcript. Any student interested in a minor in GPS is urged to contact the appropriate 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 109, which must be approved by the appropriate option representative.

HISTORY OPTION AND MINOR (H)

Students who choose the history option will learn how to *do* history—how to think critically about past societies and their development, how to read evidence closely, and how to express arguments in writing. With the guidance of a faculty adviser in history, students taking the option will explore the range of human experience in the realms of politics, culture, religion, and economics, as well as science and technology. They will learn both to challenge and revise existing historical narratives and question their own ideas and assumptions about the past. Students will develop the writing skills that will enable them to use historical sources to make effective arguments, and they will receive extensive feedback on their writing from their adviser and from other faculty members.

The history option thus provides science and engineering students with an important supplement to the scientific training and technical skills they acquire in other courses and options. It will help them to understand the world of human beings and human behavior outside of science with which they will interact and which their scientific work will affect; to set themselves and their work as scientists and engineers in this wider context; and to communicate what they are doing to a wider public as well as to their colleagues. 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 (which may include a freshman humanities course in history) 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. History majors may also choose to take one term of H 98, an individual program of directed reading that will allow students to explore areas of history not covered by regular courses.

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.

In the senior tutorial, students will have the opportunity over the course of three terms to explore in depth an historical subject of particular interest to them, while working one-on-one with a member of the history faculty. They will learn how to carry out historical research, in libraries as well as on-line, and engage critically with both primary and secondary historical sources. Finally, they will learn, under the direct supervision of their faculty mentor, to organize and to write an extensive research paper, of at least 30 pages, that makes an original, clear and persuasive scholarly argument. In H 99a, students will carry out general research in their area of interest, and identify the specific topic on which they wish to write. In H 99b they will learn to frame a research question, carry out independently the necessary research to answer it, and generate an outline of their paper. In H 99c they will write and revise their paper in response to feedback from their faculty mentor.

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 a freshman humanities course in history (courses cross-listed Hum/H numbered 50 or below). 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.

H Option Requirements

1. H 99 abc.
2. 72 additional units of history courses numbered 99 or above. Up to nine units of freshman humanities in history (courses cross-listed Hum/H numbered 50 or below) 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/Wr 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.

H 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 freshman humanities in history (courses cross listed Hum/H numbered 50 or below) may be substituted for
3. any nine of the 72 units required for the minor.
4. Nine units of H 98 may be substituted for any nine of the 72
5. 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 (HPS)

The history and philosophy of science option (HPS) provides students the opportunity to 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 courses in history help students learn about 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, chemistry, geography and cartography, medicine; and biographical and comparative studies in these fields. HPS courses in philosophy deal with issues in causation and explanation; the foundations of probability and statistical inference; and philosophical problems in particular fields such as biology, mathematics, medicine, neuroscience, and physics. In their coursework, students receive regular feedback from the faculty on their research, writing, and presentation skills. They have the opportunity to carry out independent research, especially in their thesis work, and present their findings in a seminar setting.

This option thus aims to give students a broad, basic understanding of how science is practiced and how that practice has changed over time. Students learn to address questions such as: 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? What are the ethical issues raised by experimentation with human or animal subjects? How has relativity theory changed our conceptions of space and time? The option is designed to complement the regular science curriculum at Caltech, offering students the opportunity to enlarge upon, and to contextualize, the strong technical skills they acquire in other courses and options.

Because of its emphasis on essay writing and formulating complex philosophical and historical arguments, our curriculum provides training in writing and communication skills that are increasingly vital today. The HPS option provides excellent preparation for students going into law, business, medicine, science journalism and public affairs, and it also prepares students for graduate work in the history and/or philosophy of science.

HPS Option Requirements

1. Hum/H/HPS 18; 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/H/HPS 18, Introduction to History of Science, as one of their freshman humanities courses. Students making the decision to follow this option in their sophomore year should take Hum/H/HPS 18 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:

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.

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).

HPS 102ab, the Senior Research Seminar, may be taken in any two consecutive terms in the Senior year. Students should coordinate with their HPS adviser in determining their course schedule.

HPS Typical Course Schedule

First Year

It is recommended that students intending to follow the HPS option take Hum/H/HPS 18 as one of their freshman humanities courses.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
HPS 18[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 or PS 12	Introductory Social Science	9	-	-
	Other electives	27	36	27
	Total	**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
	Total	**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
	Total	**46**	**40**	**40**

[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 they 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)

[3] Finally, HPS 102 ab, Senior Research Seminar, may be taken in any two consecutive terms in the senior year. Students should coordinate with their HPS adviser in determining their course schedule.

HPS 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. Freshman Humanities courses other than Hum/H/HPS 18 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 com-

pleting 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 18 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.

INFORMATION AND DATA SCIENCES (IDS)

The information and data sciences are concerned with the acquisition, storage, communication, processing, and analysis of data. These intellectual activities have a long history, and Caltech has traditionally occupied a position of strength with faculty spread out across applied mathematics, electrical engineering, computer science, mathematics, physics, astronomy, economics, and many others disciplines. In the last decade, there has been a rapid increase in the rate at which data are acquired with the objective of extracting actionable knowledge—in the form of scientific models and predictions, business decisions, and public policies. From a technological perspective, this rapid increase in the availability of data creates numerous challenges in acquisition, storage, and subsequent analysis. More fundamentally, humans cannot deal with such a volume of data directly, and it is increasingly essential that we automate the pipeline of information processing and analysis. All areas of human endeavor are affected: science, medicine, engineering, manufacturing, logistics, the media, entertainment. The range of scenarios that concern a scientist in this domain are very broad—from situations in which the available data are nearly infinite (big data), to those in which the data are sparse and precious; from situations in which computation is, for all practical purposes, an infinite resource to those in which it is critical to respond rapidly and computation must thus be treated as a precious resource; from situations in which the data are all available at once to those in which they are presented as a stream.

As such, the information and data sciences now draw not just upon traditional areas spanning computer science, applied mathematics, and electrical engineering—signal processing, information and communication theory, control and decision theory, probability and statistics, algorithms—but also a range of new contemporary topics such as machine learning, network science, distributed systems, and neuroscience. The result is an area that is new, fundamentally different that related areas like computer science and statistics, and that is crucial to modern applications in the physical sciences, social sciences, and engineering.

The Information and Data Sciences (IDS) option is unabashedly mathematical, focusing on the foundations of the information and

data sciences, across its roots in probability, statistics, linear algebra, and signal processing. These fields all contribute crucial components of data science today. Further, it takes advantage of the interdisciplinary nature of Caltech by including a required set of application courses where students will learn about how data touches science and engineering broadly. The flexibility provided by this sequence allows students to see data science in action in biology, economics, chemistry, and beyond.

In addition to a major, the IDS option offers a minor that focuses on the mathematical foundations of the information and data sciences but recognizes the fact that many students in other majors across campus have a need to supplement their options with practical training in data science.

IDS Option Requirements
1. *Computer Science Fundamentals.* CS 1; CS 2; and CS 38.
2. *Mathematical Fundamentals.* Ma 2; Ma 3; Ma 108a; and Ma/CS 6ab or Ma 121ab. The analytical tracks of Ma1bc are required.
3. *Scientific Fundamentals.* 18 units selected from the following courses Bi 8, Bi 9, Ch 21abc, Ch 24, Ch 25, Ch 41abc, Ph 2abc, or Ph 12abc. Advanced 100+ courses in Bi, Ch, or Ph with strong scientific component can be used to satisfy this requirement with approval from the option administrator, but cannot simultaneously be used to satisfy the "Applications of Data Science" requirement or the "Advanced Electives" requirement.
4. *Communication Fundamentals.* SEC 10; SEC 11, SEC 12, or SEC 13.
5. *Information and Data Science Core Requirements.*
   a. Linear Algebra: ACM/IDS 104; ACM 106a.
   b. Probability: ACM/EE/IDS 116.
   c. Statistics: IDS/ACM/CS 157.
   d. Machine Learning: CMS/CS/CNS/EE/IDS 155 or CS CNS/EE 156a.
   e. Signal Processing: EE/IDS 111.
   f. Information Theory: EE/IDS 160
6. *Applications Electives.* At least 18 units from the following list: Ay 119, BE/Bi 103 ab, Bi/BE/CS 183, BEM/Ec 150, CNS/Bi/EE/CS/NB 186, ME/CS/EE 134, EE/CNS/CS 148, Ec/SS 124, ESE 136, Fs/Ay 3, Fs/Ph 4, Ge/Ay 117, Ge 165, HPS/Pl/CS 110, SS 228. Other courses that include applications of data science may be substituted with approval from the option coordinator. Courses used to fulfill this requirement may not also be used to fill the any requirement above
7. *Advanced Electives.* At least 54 units from the following list: IDS courses numbered 100 or above, CS/CNS/EE 156ab, ACM 106b, ACM 95/100ab. Courses used to fulfill this requirement may not also be used to fill the any requirement above.

Courses used to fulfill requirements in the "Applications of Data Science" and "Advanced Electives" requirements cannot be used to fulfill the institute humanities and social sciences requirements.

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 total of 486 units, including all courses used to satisfy the above requirements.

IDS Double Majors

Students interested in simultaneously pursuing a degree in a second option must fulfill all the requirements of the Information and Data Sciences option. Courses may be used to simultaneously fulfill requirements in both options. However, it is required that students have at least 54 units of "Advanced Electives" and 18 units of "Applications of Data Science" that are not simultaneously used for fulfilling a requirement of the second option, i.e., the requirements of the Advanced Electives and the Applications of Data Science sections must be fulfilled using courses that are not simultaneously used for fulfilling a requirement of the second option. Any proposal to replace these courses must be discussed with the option administrator. 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.

IDS Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
CS 1	Intro. to Computer Programming	9	-	-
CS 2	Intro. to Programming Methods	-	9	-
CS 38	Algorithms	-	-	9
Ma 2	Differential Equations	9	-	-
Ma 3	Intro. to Probability and Statistics	-	9	-
Ma/CS 6 ab	Intro. to Discrete Methods	9	9	-

ACM/IDS 104	Applied Linear Algebra		9	-	-
	HSS Electives		9	9	9
	Scientific Fundamentals		-	9	9
	Other Electives		-	-	9
		Total	**45**	**45**	**36**
Third Year					
SEC 10	Technical Seminar Presentations		-	3	-
CMS/CS/ CNS/EE/IDS 155	Machine Learning & Data Mining		-	12	-
SEC 11, SEC 12, or SEC 13	Written Communication		-	-	3
Ma 108 a	Classical Analysis		9	-	-
EE/IDS 111	Signal-Processing Systems and Transforms		9	-	-
IDS/ACM/CS 157	Statistical Inference		-	-	9
ACM/EE/IDS 116	Intro. to Probability Models		9	-	-
	HSS Electives		9	9	9
	Advanced Electives		9	9	9
	Applications Electives		-	9	-
	Other Electives		-	-	9
		Total	**45**	**42**	**39**
Fourth Year					
ACM/EE 106 a	Intro. Methods of Computational Math.		12	-	-
EE/IDS 160	Fundamentals of Information Transmission and Storage		-	9	-
	Advanced Electives		9	9	9
	Applications Electives		9	9	-
	HSS Electives		9	9	9

303

Other Electives	9	9	18
Total	**48**	**45**	**36**

IDS Advising

Starting in the sophomore year IDS students will be assigned a faculty adviser whom they should meet with regularly, typically once per quarter. Students in the program are advised by faculty interested in the information and data sciences from across the institute. This includes all the CMS faculty, as well as the following faculty that pursue data science-related research and participate in IDS advising: Justin Bois, Fernando Brandao,Shuki Bruck, George Djorgovski, Laura Doval, Frederick Eberhardt, Federico Echenique, Babak Hassibi,Jonathan Katz, Victoria Kostina, Heather Knutson, Tom Miller, Pietro Perona, Antonio Rangel, Mark Simons,Omer Tamuz, Andrew Thompson, Matt Thomson, Victor Tsai, David Van Valen, Zhongwen Zhan. Students seeking an IDS adviser should contact the undergraduate option secretary at academics@cms.caltech.edu.

IDS Minor Requirements

1. *Computer Science Fundamentals.* CS1; CS2; and CS38.
2. *Mathematics Fundamentals.* Ma 3, Ma/CS 6a or Ma 121a.
3. *Information and Data Science Core Requirements.*
   a. Probability: ACM/EE/IDS 116.
   b. Linear Algebra: ACM/IDS 104.
   c. Statistics: IDS/ACM/CS 157.
   d. Machine learning: CMS/CS/CNS/EE/IDS 155 or CS/CNS EE 156a.
   e. Signal Processing: EE/IDS 111
4. *Applications of Data Science.* At least 9 units from the following list: Ay 119, BE/Bi 103 ab, Bi/CNS/NB 153, Bi/CNS/NB 162, Bi/BE/CS 183, BEM/Ec 150, CNS/Bi/EE/CS/NB 186, ME/CS/EE 134, EE/CNS/CS 148, Ec/SS 124, ESE 136, Fs/Ay 3, Fs/Ph 4, Ge/Ay 117, Ge 165, HPS/Pl/CS 110, SS 228. Other courses that include applications of data science may be substituted with approval from the option coordinator.
5. *Advanced Electives.* At least 9 units from the following list: IDS courses numbered 100 or above, CS/CNS/EE 156ab, ACM 106b, ACM 95/100ab. Courses used to fulfill this requirement may not also be used to fill the any requirement above.

Courses used to fulfill requirements in the "Applications of Data Science" and Advanced Electives" requirements cannot be used to fulfill (i) a requirement for another major or minor; or (ii) the institute humanities and social sciences requirements. Any replacement of these courses must be discussed with the option administrator.

Pass/fail grading cannot be elected for courses taken to satisfy option requirements. Courses taken as part of the data science

minor are counted toward the total 486 units needed for Institute graduation requirements.

Typical course schedule
A typical course sequence is to take CS 1 during freshman year; Ma/CS 6a, Ma 3, CS2 and CS38 during sophomore year; ACM/EE/IDS 116, ACM/IDS 104, CMS/CS/CNS/EE/IDS 155, and IDS/ACM/CS 157 during junior year; and EE/IDS 111 and the elective courses during senior year.

INTERDISCIPLINARY STUDIES PROGRAM (ISP)

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.

ISP 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 advisers 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.

MATERIALS SCIENCE OPTION (MS)

The aim of the Materials Science option is to prepare students for research, professional practice, or advanced study in a rapidly advancing interdisciplinary field, focusing on the relationships between the properties of materials and their internal structure and how this structure can be controlled. The program builds on the core curriculum to develop analytical competence and use it for individualized research, culminating in a one-year senior thesis. Materials Science students develop professional independence, creativity, leadership, and the skills 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 Materials Science option are assigned advisers appropriate for their expressed field of interest. 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 Materials Science option requires one year of applied and computational mathematics and a prescribed number of units selected from a wide variety of courses in science and engineering. An undergraduate thesis is an essential part of the academic program. Any student in the Materials Science 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 Materials Science option.

MS Option Requirements

1. Fulfillment of extended core requirements in Differential Equations (Ma 2 or equivalent); Probability and Statistics (Ma 3, Ge/ESE 118 or equivalent); Waves (Ph 2a, Ph 12a or equivalent), Quantum Mechanics (Ph 2b, Ph 12b, Ch 21a or equivalent); Thermodynamics and Statistical Mechanics (Ph 2c, Ph 12c or equivalent).

2. Demonstration of competency in computer programming or computer science by taking CS 1, or by taking an approved alternative course, or by passing a placement exam administered by the computer science option.
3. 9 units of laboratory courses taken from the following list: APh 77 bc, Ae/APh 104 bc, CE 180, CS/CNS 171, CS/CNS 174, EE 45, , EE/CS 53, EE 90, EE 91 ab, ME 72 ab, ME 50ab, MS 121, MS/APh 122, MS 125, MS 142.
4. 9 units of additional laboratory courses either from the list above or from EAS courses with the word "laboratory" in the title, but excluding those courses for which freshman laboratory credit is allowed.
5. ACM/IDS 104 and ACM 95 ab, or Ma 108 abc, or Ma 109 abc.
6. SEC 10 or equivalent; SEC 11, SEC 12, SEC 13 or equivalent.
7. APh 17 ab or ChE 63 ab or APh/MS 105 ab.
8. MS 115 and MS/ME/MedE 116 and MS 90 (or other appropriate laboratory in MS).
9. At least 45 of additional units from the following list of restricted electives: ACM/IDS 104, Ae/AM/CE/ME 102 abc, APh/MS 105 abc, APh 114 abc, APh/EE 130, APh/EE 183, Ch 21 abc, Ch 120 ab, Ch 121 ab, Ch 125 abc, Ch/ChE 147, ChE/Ch 148, CS 11, Ge 114 ab, ME 12 abc, MS 121, MS 122, MS 125, MS 131, MS 132, MS 133, MS 142, Ph 125 abc. Substitution of courses may be approved at the discretion of the option representative.
10. Senior thesis MS 78 abc.

Passing grades must be earned in at least 486 units, including those listed in requirements 1–10 above.

MS Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
CS 1	Intro. to Computer Programming	9	-	-
Ma 2	Differential Equations	9	-	-
Ma 3	Intro. to Probability and Statistics	-	9	-
MS 90	Materials Science Laboratory	-	-	9
MS 115	Fundamentals of Materials Science	9	-	-
MS 116	Mechanical Behavior of Materials	-	9	-
Ph 2 abc or Ph 12 abc	Waves, Quantum Mechanics and Statistical Physics	9	9	9
	HSS Electives	-	9	18
	Total	**36**	**36**	**36**
Third Year				
ACM/IDS 104	Applied Linear Algebra	9	-	-
ACM 95 ab	Intro. Methods of Applied Math.	-	12	12
APh 105abc	States of Matter	9	9	9
MS 131	Structure and Bonding in Materials	-	9	-
MS 132	Diffraction and Structure	9	-	-
MS 133	Kinetic Processes in Materials	-	-	9
	HSS Electives	9	9	9
	Lab Class	9	9	-
	Restricted Electives (from 11)	-	9	9
	Total	**45**	**48**	**48**
Fourth Year				
SEC 10	Technical Seminar Presentation	3	-	-

SEC 11, SEC 12, or SEC 13	Written Communication	-	3	-
MS 78abc	Senior Thesis	9	9	9
	HSS Electives	9	9	9
	Lab Class	9	-	-
	Restricted Electives	18	18	18
	Total	**48**	**39**	**36**

MATHEMATICS OPTION (Ma)

The mathematics option is designed to give students an understanding of the broad outlines of modern mathematics, to introduce current research and to prepare them for advanced work in pure mathematics or related fields. Math students go well beyond the basics to study the structures of algebra, analysis and geometry, as well as the rudiments of combinatorics and set theory. Students learn to write coherent and complete proofs of various assertions, to work out non-trivial examples and to use computational tools.

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. Some students go to use their background in mathematics as an entry to other fields, such as physics, computer science, statistics, economics, business, finance, medicine and law.

Freshmen considering majoring in mathematics should be aware that the department strongly recommends taking the analytical track of Ma 1 bc. Any 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 be refused permission to continue work in the mathematics options.

Ma Option Requirements

1. Ma 2.
2. Ma 3 or Ma 140 a.
3. Ph 2 bc or Ph 12 bc
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 of Ma numbered 110 to 190 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 undergraduate option representative

for mathematics. Of these 45 units, at most 18 can be from courses other than 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 include courses taken to satisfy requirements 2, 5, 6 or 7.

9. Requirements 1– 6 may not be taken pass/fail unless completed during fall or winter of freshman year or when the course is only offered as pass/fail.

10. Passing grades must be earned in a total of 486 units, including the courses listed above.

Ma Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2, 3	Sophomore Mathematics	9	9	-
Ph 2 bc or 12 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
	Total	**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
Ma 110-190/ ACM 95+	Advanced Mathematics	9	9	9
	HSS Electives	9	9	9
	Electives[1]	9	18	9
	Total	**48**	**45**	**45**

Fourth Year

Ma 11	Mathematical Writing	-	-	3
Ma 109 abc	Introduction to Geometry and Topology	9	9	9
Ma 110-190/ ACM 95+	Advanced Mathematics	9	9	-
	HSS Electives	9	9	9
	Electives[1]	18	18	18
	Total	**45**	**45**	**39**

[1] *Includes courses completed to fulfill option requirements 5, 6 and 7.*

MECHANICAL ENGINEERING OPTION (ME)

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.

ME Option Requirements
1. Technical communication: SEC 10 and one of SEC 11, SEC 12, or SEC 13.
2. Mathematics: Ma 2, ACM 95ab, and 9 units selected from Ma 3, Ma 6a, ACM 104, or other ACM courses numbered 100 and above.
3. Physics: 18 units selected from Ph 2abc.
4. Computing: 9 units selected from ACM 11, CS 1, CS 2, CS 11.
5. ME Core: ME 10, ME 11 abc, ME 12 abc, ME 13, ME 14, ME

40 (BE / Bi 103 and Ge/ESE 118 are acceptable substitutions for 2019-20), and ME 50 ab.
6. Capstone design: ME 72 ab or ME 90 abc or CS/EE/ME 75 abc.*
7. 45 units of advanced engineering electives selected from a list of approved courses or from courses pre-approved by the Option Representative. 27 units must be from one track (depth requirement) and at least 9 units from two other tracks (breadth requirement).**
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 adviser and typically taken in the third and fourth years. Please consult the Mechanical and Civil Engineering website and / or the adviser for further information.*

ME Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
Ma 2	Differential Equations	9	-	-
	Computing Elective	9	-	-
ME 10	Thinking Like an Engineer	1	-	-
ME 11 abc	Thermal Science	9	9	9
ME 12 abc	Mechanics	9	9	9
ME 13	Mechanical Prototyping	-	4	-
ME 14	Design and Fabrication	-	-	9
ACM 95 ab	Intro. Meth. Applied Math.	-	12	12
	HSS electives	9	9	-
	Total	**46**	**43**	**39**
Third Year				
	Physics Electives	9	-	9
ME 50 ab	Exp. and Modeling in ME	-	9	9
ME 40	Dimensional and data analyses in engineering	9	-	-
	Capstone Design	9	9	-

SEC 10	Technical Seminar Presentation	-	-	3
SEC 11, SEC 12, or SEC 13	Written Communication	3	-	-
	HSS Electives	9	18	9
	Total	**39**	**36**	**30**

Fourth Year

	Math Electives	9	-	-
	Advanced ME electives	18	18	9
	HSS electives	9	9	9
	Total	**36**	**27**	**18**

PHILOSOPHY OPTION AND MINOR (PI)

The philosophy option provides students with a broad education in philosophy that is designed to complement the scientific curriculum at Caltech. Philosophy majors will be expected to learn about some of the major figures and movements in the history of philosophy, and to learn about contemporary philosophical debates. The philosophy option also aims 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.

The philosophy curriculum will help students to acquire the basic tools of philosophical analysis: the ability to read and interpret philosophical texts; the ability to identify strengths and weaknesses of philosophical arguments; the ability to develop well-reasoned defenses of philosophical positions; and the ability to anticipate objections to one's own views. In addition, the philosophy option will train students to express themselves clearly and concisely in both writing and speaking. These critical thinking and communication skills provide an excellent foundation for any intellectual endeavor, and are critical to those pursuing careers in fields such as law, business, medicine, and scientific research.

The courses in the philosophy option concentrate in four major areas: philosophy of science; philosophy of mind, brain, and behavior; history of philosophy; and ethics. In their coursework, students will have the opportunity to discuss and debate philosophical issues in small groups, and will learn how to offer and receive constructive criticism. They will also receive detailed feedback on their persuasive writing from several different members of the philosophy faculty.

In their senior thesis, philosophy majors will have the opportunity to pursue more intensive research in one particular area of

philosophy, and to sustain an argument on a larger scale, while working one-on-one with a member of the philosophy faculty. This will provide interested students with a solid foundation for graduate work in philosophy and related fields.

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 freshman humanities in philosophy (courses cross-listed Hum/Pl numbered 50 or below), 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 specific 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 as part of their 99-unit requirement.

Students considering the philosophy option will be well advised to take a freshman humanities course in philosophy. 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- to 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 Pl 98 and courses taken during the first two quarters of the 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.

Pl Option Requirements

1. Pl 90 ab.
2. 63 units of advanced philosophy courses, numbered 99 or above. Up to nine units of freshman humanities in philosophy (courses cross-listed Hum/Pl numbered 50 or below) 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 advis-

er. 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. Three units of oral communication. En 84 satisfies this requirement, as do oral communication courses offered by other options.

6. 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.

Pl 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. 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 Pl 98 and courses taken during the first two semesters of freshman year, all courses to be counted toward the philosophy option or 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 freshman humanities in philosophy (courses cross-listed Hum/Pl numbered 50 or below) 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 (Ph)

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-lev-

el courses give a thorough treatment of fundamental principles. Elective courses taken during the junior and senior years allow students to explore their particular interest. Some electives offer broad surveys, while others concentrate on particular fields of current research. A choice of laboratory course is offered at several levels. Students interested in concentrating their studies in one specific area of physics should refer to the undergraduate physics website for course schedule recommendations.

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.

Ph Option Requirements

The first five requirements should be completed by the end of the second year. In planning 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 or APh/EE 24.[2]
6. 27 units of Ph 78 (experimental), or 18 units of Ph 77, or 9 units of Ph 77 and 9 units from APh 77 or Ay 105, or 9 units of Ph 77 and 9 units of Ph 177.
7. Ph 70.[3]
8. Ph 106 ab.
9. Ph 125 ab.
10. Ph 127 a.
11. Ph 21 or Ph 22 or one term of Ph 121 abc or Ay 190.

[1] Other laboratory courses may be substituted for the Ph 3 requirement, including Ph 5, Ph 8 bc, or APh 9 a.

[2] APh 23 is a prerequisite for APh/EE 24 and can be used towards the advanced physics elective requirement.

[3] Other communication courses e.g., Ay 30 (or Ay 141) and 31 or Ma 10 and 11 may be substituted for Ph 70.

Ph Required Electives

1. 90 units of Advanced Physics Electives, in addition to the above, include any of the following: any Ph, APh, or Ay, course numbered 100 or above, or any of Ph 5, Ph 22, Ph 78, ACM 95, ACM 101, APh/EE 23, Ma 5, Ma 108, or up to 10 units for Ay 20 – 21. Nine units towards 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 for any courses used for this requirement with the exception of ACM 95 and courses that do not offer grades. Not 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 171-172 may apply toward this requirement without permission from the Undergraduate Option Representative. Additionally, Ph 171-172 may only apply toward this requirement if taken in increments of six units or more and a written summary (2-4 pages in length) of the work completed is submitted to the Undergraduate Option Representative within 2 weeks of the beginning of the subsequent quarter. Students may also petition the Undergraduate Option Representative to request that courses from other options with suitable physics content apply toward this requirement.

2. Nine units of science and 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.

Ph 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	-
Ph 6, Ph 7	Physics Laboratory	-	9	9
ACM 95 ab	Intro. Methods of Applied Math	-	12	12
Ph 21/22	Computational Physics	-	-	6
	HSS and/or PE Electives	18	9	9
	Science/Engineering Electives	9	-	-
	Total	**45**	**48**	**45**
Third Year				
Ph 106 ab	Topics in Classical Physics	9	9	-
Ph 121 abc	Advanced Computational Physics	6	6	6

Ph 125 ab	Quantum Mechanics	9	9	-
Ph 70	Oral & Written Communication	6	-	[6]
	HSS and/or PE Electives	9	9	9
	Advanced Physics Electives	9	12	33 [27]
	Total	**48**	**45**	**48**

Fourth Year

Ph 77 abc	Advanced Physics Laboratory	9	9	-
Ph 127 a	Statistical Physics	9	-	-
	Advanced Physics Electives	9	9	18
	Electives	9	18	18
	HSS and/or PE Electives	9	9	9
	Total	**45**	**45**	**45**

POLITICAL SCIENCE OPTION (PS)

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, law, or public policy. Students who complete the political science option can expect the following learning outcomes:

- an understanding of and ability to use the theoretical tools of social choice and game theory as applied to politics;
- an understanding and knowledge of how to apply quantitative methods to study politics;
- the ability to present complex theoretical and quantitative material in research reports and presentations; and the skills necessary to pursue graduate education and careers in law, government, politics, or public policy.

Note: The official source on requirements for graduation is the Caltech catalog from the year in which a student began studies at Caltech. Please see the catalog online, from this and previous years, for information regarding the applicable option requirements.

PS Option Requirements

1. PS 12, PS 132, Ec 122.
2. Four political science courses from the list: PS 120, 123, 130, 135, PS/SS 139, PS 141ab, Law/PS/H 148 ab, or 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.

PS Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
Ma 3	Probability & Statistics	-	9	-
PS 12	Introduction to Political Science	9	-	-
PS 132	Formal Theories in Political Science	9	-	-
EC 122	Econometrics	9	-	-
	Electives	18	36	45
	Total	**45**	**48**	**45**
Third Year				
	Political Science Electives [1]	18	18	18
	Electives	27	27	27
	Total	**48**	**45**	**45**
Fourth Year				
PS 99 ab	Research in Political Science	-	9	9
	Political Science Electives [1]	18	18	18

Electives	27	18	18
Total	**45**	**45**	**45**

[1] *See option requirements 2, 5, and 6.*
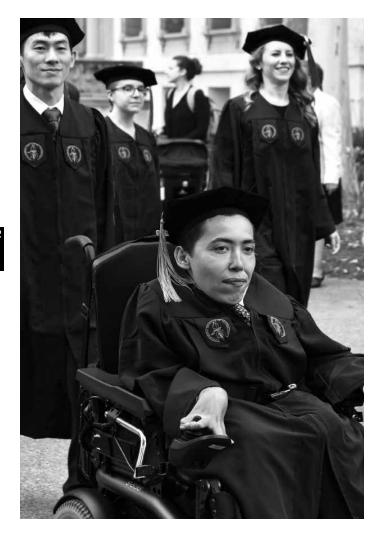
STRUCTURAL MECHANICS MINOR (SM)

This minor is intended to supplement one of Caltech's under-graduate degrees and is designed for students who wish to broad-en 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 mechan-ics minor requirements will have the phrase "minor in structural mechanics" added to their academic transcripts.

SM Minor Requirements

The student must complete 54 units of classes selected from Ae/AM/CE 102 abc, AM/CE 151, Ae/CE 221, Ae/CE 165ab 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.

Information for Graduate Students

The Institute offers graduate degrees of Master of Science and Doctor of Philosophy, and in special cases the degree of Engineer.

The Institute is organized into 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.

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.

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. A list of the option representatives for the current academic year can be found at www.registrar.caltech.edu/academics /grad_option_reps.

GRADUATE POLICIES AND PROCEDURES

ADMISSION TO GRADUATE STANDING

Application

An application for admission should be completed online through the Graduate Office at www.gradoffice.caltech.edu/admissions. Admission is granted once a year to a limited number of students of superior ability. Completed applications are due between December 1 and January 1, for enrollment at the beginning of the fall term of the following year. Please refer to the Graduate Office website for specific deadlines. The graduate program thrives on exceptional individuals from a diverse range of backgrounds and experiences, and we highly encourage applications from members of groups underrepresented in science and engineering. Graduate admission is covered by Caltech's Nondiscrimination Policy. For more information on this policy, please refer to page 92. Applicants will automatically be considered for financial aid; no additional application is required.

To be admitted to graduate standing, an applicant must have received a bachelor's degree, or the equivalent, representing the completion of an undergraduate course in science or engineering related to one of the options offered by the Institute. Applicants

must, moreover, have attained a scholastic record and provide recommendations to indicate the fitness to pursue, with distinction, advanced study and research.

Required Tests

Graduate Record Examination (GRE) verbal, quantitative, and writing scores and advanced subject GRE scores may be optional, recommended or required depending upon the option requirements as part of the application for graduate admission. Applicants should refer to the Graduate Office website for additional details.

A test of English proficiency is required for applicants who are non-native English speakers. See below for details.

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. 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 or have not received a degree from a university or college where English is the primary language of instruction are required to take a test of English proficiency as part of the application process. 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 (institutional code 4034) prior to the relevant application deadline. Testing schedules and information on the TOEFL may be obtained online at www.toefl.org. Testing schedules and information on the IELTS exam may be obtained online at www.ielts.org.

Students who do not achieve a high score on these tests, or who have had little opportunity to communicate in English, are highly recommended to make arrangements for intensive work during the summer preceding their registration. All international students are evaluated upon arrival at Caltech and, if it is determined that additional instruction in English is needed, they will be assigned to an English as a Second Language (ESL) course.

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 and are current graduate students at another institution. The invitation process requires sponsorship by a Caltech faculty member, and requests should be made directly to

the Graduate Office, following the visiting student instructions on the Graduate Office website. The Dean of Graduate Studies may limit the number of visiting students in any given year. Visiting students are subject to the Honor System (see page 20) and other Institute policies and are under the purview of the Dean of Graduate Studies. Visiting students are categorized into two main classifications.

Special Students

Special Students 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 Student appointments are allowed for one year, renewable each year up to a maximum of three years. 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 eligible for the same privileges as regularly enrolled graduate students, and will be billed for tuition and fees. Short-term Special Students that do not need academic credit must still enroll in a research class for a minimum number of units and will be billed tuition and fees based on the level of enrollment and the length of stay. 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 a reduced tuition and fees rate. (For current rates, see the expense summary on page 349.)

325

Visiting Student Researchers

The Visiting Student Researcher status is limited to short-term visits of one month to one year and is not renewable. Visiting Student Researchers are not eligible to enroll in a research course and/or coursework, and will not receive academic credit from Caltech, but will receive a Caltech identification card. Visiting Student Researchers are also required to provide proof of health insurance and any required medical and immunization records for the duration of the visit.

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 must be appointed as Special Students.

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 completion of a greater number of units in any one term will not be regarded as increasing the residence. In general, the residency requirements are as follows: for Master of Science, a minimum of three terms of enrollment; for the degree of Engineer, a minimum of eight terms of enrollment; and for Doctor of Philosophy, a minimum of 12 terms of enrollment, four of which must be at the Institute.

REGISTRATION

Graduate students are required to register for each term, including summer, whether they are taking classes, conducting research, doing independent reading, writing a thesis, or utilizing any other academic service or campus facility.

A graduate student must be registered for a minimum of 36 research and/or course units to be classified as a full-time student, and may not enroll in excess of 36 research units. A graduate student who registers for less than 36 total 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 in advance 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 their major work. See the section on Satisfactory Academic Progress for more information.

In registering for research, students should indicate the name of the instructor in charge, and should consult with the instructor 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 the instructor 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 are 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 those courses 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 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 the 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 each term, including the summer. They are entitled to at least two weeks' annual vacation (in addition to Institute holidays), and they should arrange their vacation 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, a minimum of 36 units must be taken during each term of enrollment.

GRADUATE STUDENT LEAVES OF ABSENCE

General Administrative Requirements

Graduate students are required to have continuity in registration, maintain 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 either be registered, enrolled or on an approved leave from the Institute. Reduced duty status maintains registration for a student who cannot carry a full load due to a medical condition, disability or pregnancy.

Registration is required for the term in which the thesis defense is undertaken, with the exception of the first week of each term. Approval of the Dean is required for any student seeking to enroll for subsequent terms beyond the defense during the academic year. Once the degree is conferred, further enrollment as a graduate student is not permitted.

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.

Petitions for Leave

Petition forms for leaves may be obtained from the Graduate Office website and must, before submission to the Dean, carry the acknowledgment of the student's option representative and, where appropriate, the thesis adviser. Petitions for medical leave must carry the recommendation of the Executive Director of Student Wellness Services or their designee. In case of a lapse in status, readmission must be sought before academic work may be resumed or requirements for the degree completed.

While on Leave

A student on a personal, medical or involuntary leave may not attend classes, live in Institute housing, participate in Institute programs, use Institute facilities, work on campus, or use student resources such as Student Wellness Services, Center for Diversity, Career Services or the Center for Teaching, Learning, and Outreach (CTLO) during the leave, unless approved in writing by the Dean.

Voluntary Leaves

Personal Leaves

A student may request a voluntary leave of absence for personal reasons by submitting a personal (non-medical) leave petition to the Graduate Office for approval. International students should consult with the International Student Programs (ISP) office regarding visa implications prior to submitting the leave petition.

The Dean may grant a personal leave provided (a) the student is

making satisfactory academic progress as determined by the student's adviser, (b) the leave is for one year or less, although special circumstances can be considered for a longer leave, and (c) the leave extends over a period that includes at least one full term.

A petition to return from a personal leave should be submitted six (6) weeks before the first day of the term for which the student intends to return. Return from a personal leave is subject to the approval of the Dean and is subject to the student having an approved adviser and ongoing funding to support the student's research. If a student does not anticipate having an adviser upon return, they will need to work with the option representative to arrange for funding and a new adviser in advance of the return. Return will only be granted once an adviser and funding are in place.

Medical Leaves

If a student is unable to complete their coursework or other course of study due to medical reasons, the student may petition for a medical leave of absence by submitting a medical leave petition to the Graduate Office for approval. The petition for medical leave must be recommended by the Executive Director of Student Wellness Services or their designee. International students should consult with the International Student Programs office regarding visa implications prior to submitting the medical leave petition.

Medical leaves are expected to extend over a period that includes at least one full term, although special circumstances may be considered for approval of a shorter leave upon the recommendation of a student's treatment team.

Students must provide documentation of the need for the leave by a licensed health care provider. Students may be required to sign a release of information form authorizing their health care provider to communicate relevant medical information to representatives within Student Wellness Services and the Graduate Office to facilitate evaluation of the need for the leave and to determine appropriate conditions associated with the leave and return from the leave.

The Institute may impose conditions on return from a medical leave, which may include confirmation from the student's health care provider that the student is following the recommended course of treatment, the student's consent for the provider to discuss the student's condition or progress during the leave with Caltech officials, including representatives of Student Wellness Services and the Graduate Office, and an independent evaluation of the student's readiness to return by a qualified medical professional. Any conditions of return will be specified at the time of the leave approval.

A petition to return from medical leave must be submitted six (6) weeks before the anticipated term for which the student intends to return. The return process includes an interview with the Executive

329

Director of Student Wellness Services or their designee and the submission of a completed return from medical leave petition and provider recommendation. Students are expected to sign a release of information form authorizing their treatment providers to communicate with Caltech, including representatives of Student Wellness Services and the Graduate Office to determine readiness to return and any recommendations for reasonable accommodations. Return from a medical leave of absence is subject to the final approval of the Dean.

A student returning from a leave for medical reasons will maintain the same academic standing that they had prior to the leave. Additional information and resources regarding medical leave, including financial and transcript implications, can be found at https://www.gradoffice.caltech.edu/current/LeavePolicy.

Pregnancy

Consistent with Caltech policy, the requirements of Title IX, and Section 66281.7 of the California Education Code, students who are unable to complete their coursework or other course of study for a period of time due to a pregnancy, childbirth and related medical conditions are eligible for a pregnancy leave of absence. Students who are pregnant or who have recently given birth are also eligible for reasonable accommodations.

Students are not required to take a leave of absence, withdraw, or limit their graduate studies because of pregnancy, childbirth or related medical conditions. However, students who are disabled due to pregnancy, childbirth and related medical conditions are eligible to take a pregnancy leave of absence. The Institute provides up to six (6) weeks of pay to students during a pregnancy leave of absence; an additional 6 weeks of pay is available through family bonding leave (see following section).

A pregnant student who wishes to take a pregnancy leave should submit a pregnancy leave petition to the Graduate Office. Medical documentation from the student's treating health care provider may be required.

A student who chooses to take a leave of absence because they are pregnant or have recently given birth shall be allowed an additional period commensurate with the length of the leave, but not to exceed 12 additional months, to prepare for and take preliminary and qualifying examinations and an equal extension of time toward the normative time to degree while in candidacy for a graduate degree, unless a longer extension is medically necessary.

An enrolled student in good academic standing who chooses to take a leave of absence because they are pregnant or have recently given birth shall return to their program in good academic standing following an approved leave period of up to one academic year, subject to the administrative requirements described above, unless there is a medical reason for a longer leave, in which case standing

in the graduate program shall be maintained during that period of the leave.

The Institute also provides reasonable accommodations to pregnant students consistent with federal and state law. Reasonable accommodations may include allowing pregnant students to maintain a safe distance from hazardous substances, allowing them to make up tests and assignments that are missed for pregnancy-related reasons or excusing of absences that are medically necessary.

Bonding

Students may take six (6) weeks of family bonding leave with pay. An enrolled student in good academic standing who chooses to take a leave of absence because of the recent birth or adoption of his or her child may request a bonding leave by submitting a bonding leave petition to the Graduate Office for approval. Bonding leave is in addition to pregnancy leave, providing eligible students with a combined total of up to 12 weeks of paid leave. Students returning from an approved bonding leave shall return to his or her program in good academic standing following the leave, subject to the administrative requirements described above.

Involuntary Leave

The Dean or designee may determine that it is necessary to place a student on an involuntary leave in a variety of circumstances, including when a student demonstrates behavior that poses a threat to health or safety, causes significant disruption to the Caltech community, for the personal safety or welfare of the student involved, as an interim measure, or as a result of a disciplinary action. 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 Caltech 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 the student requires a level of care from the Institute community that exceeds the reasonable accommodations, resources and staffing that the Institute can reasonably be expected to provide for the student's well-being.

Review and Decision Process

If the conduct has been the subject of an investigation or review under an Institute process or procedure, the Dean will consider the findings and conclusions reached in that process. In other circumstances described above, in making an informed decision to place a student on involuntary leave, the Dean will conduct an individualized assessment and consider relevant information including information provided in a timely manner by the student.

The Dean may consult with other Institute personnel, including but not limited to Security and Residential Life personnel, faculty, staff and other individuals or departments. If appropriate and feasible, the Dean may seek cooperation and involvement of parents or guardians of the student.

Medical information, including medical information provided in a timely manner by the student, may be considered if the behavior is associated with a physical or mental condition. In appropriate cases, the Dean may consult with the Executive Director of Student Wellness Services or their 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 risk 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. The Dean may stipulate conditions that must be met before the student may return. An involuntary leave may be a permanent separation from the Institute (i.e. expulsion); for a specific duration; or until certain conditions have been met. If the involuntary leave is not a permanent separation, the student will be advised of the length of the leave and/or any conditions for 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 in appropriate cases medical information provided by the student, before deciding on an emergency interim leave. An emergency interim leave will remain in effect until a final decision has been made.

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 consid-

er 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 be permitted to return from a leave or will be permanently separated from the Institute.

Appeal

If a decision by the Dean to place a student on involuntary leave is imposed as a sanction resulting from a finding of responsibility under an Institute process or procedure, appeal rights and limitations, such as limitations on grounds for appeal, are governed by the applicable Institute process or procedure. In all other cases, a decision by the Dean to place a student on involuntary leave may be appealed in writing within ten days to the Vice President for Student Affairs (or 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 compatible 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 situations. Both the student and adviser have the obligation to initiate meetings as necessary to ensure the success of the relationship.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee consisting of a minimum of three professorial faculty members. This committee typically meets at least once a year beginning after candidacy or 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 (Nondiscrimination Policy, page 92; Gender-Based Misconduct, page 64, and Unlawful Harassment, page 100). 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 339) and the Student Problem Resolution Process (page 42).

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 and/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.

Non-degree 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 a 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 and approval of the employee's supervisor is required.

Part-time non-degree students are subject to the Honor System

(see page 20) and are under the purview of the Dean of Graduate Studies. They may take only courses numbered 100 or higher and 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 non-degree 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 are 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 Institutes of Health

Students that are funded through NIH grants, work with 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."

335

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 graduate 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 employment, 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 progress or full-time status. The Institute also recognizes that some students desire to gain experience as instructors or work in an educational 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 350). 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 documentation 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 completion of degree requirements.

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 Student Wellness Services as well as the permission of the Dean of Graduate Studies.

337

Detached Duty

In some cases, a student may be engaged in research at an external laboratory or research institute under the supervision of a Caltech faculty adviser, and conducting research that is directly related to their 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 integral to their thesis project and appropriate mentoring. Students on detached 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 loca-

tion. They may be paid by Caltech or through another organization. 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 valid for a limited time, less than one year, and may 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 academic progress.

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 opportunities 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, the laboratory involved commits financial support for the duration of the thesis research, and 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 training may in some cases involve full-time employment 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 thesis. 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 the thesis should be regarded as equivalent to other outside employment.

EXCHANGE PROGRAM WITH SCRIPPS INSTITUTION OF OCEANOGRAPHY

An exchange program with the Scripps Institution of Oceanography (SIO), University of California, San Diego, permits 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, 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 the appropriate research laboratories 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 the 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 Master's degree can be completed in one academic year. Students must declare candidacy for the Master'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 Master's along the way, must declare candidacy for the Master'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 will not 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 a Master'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 baccalaureate 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 Master'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 their option with a grade-point average for the approved Master'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 elsewhere 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.

Admission to M.S. Candidacy

By the third term of the academic year in which the student expects to receive the degree, candidates should have completed a plan of study in Regis, which must have the approval of the option representative and, in some cases, of the research adviser. This approved plan of study will constitute requirements for the degree. Any modifications to the plan of study must be approved by the option representative no later than two weeks before the degree is to be conferred. 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 and option representative no later than two weeks before the degree is to be conferred. For additional information and option-specific requirements, please refer to the section "Special Regulations for Graduate Options."

Joint B.S./M.S. Degree

In exceptional cases, undergraduate students may be eligible to pursue a joint B.S./M.S. program of study to be completed within the four years (12 terms) of the undergraduate program. Students should contact the graduate option representative to find out if the joint B.S./M.S. degree is offered in a particular option. If so, students must follow the normal procedures for admission to the graduate program. Students admitted to the joint B.S./M.S. degree must complete a minimum of 486 units for the B.S. program and an additional 135 units for the M.S. program with no overlapping of courses. In addition, a written plan of study must be submitted to the Registrar's Office for approval no later than the fall term of the senior year. The plan of study should provide detail of the courses that are proposed to satisfy each degree requirement within the twelve terms of the B.S. program and once approved shall constitute the requirements for the degree. Any changes to the plan require written approval by the Registrar. If not completed within the four years, students will be removed from the joint program and they, and all their courses, will be attached to the B.S. program. Students enrolled in the joint B.S./M.S. degree will be considered undergraduate students and will not be eligible for graduate financial aid, graduate housing, or other graduate student privileges.

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 Ph.D. 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 be admitted for the Ph.D.

Residence

At least eight terms of graduate residence subsequent to a Bachelor's 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 somewhat longer time on graduate work.

To qualify for an Engineer's degree, a student must complete the work prescribed by the supervising committee with a grade-point average of at least 1.9. Research work and the preparation 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 their 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 comprised of at least three members of the professorial faculty to supervise the student's work and to certify its satisfactory completion. The student should consult with this committee in planning the details of their 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 requirements 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 a thesis in accordance with the regulations that govern the preparation of doctoral dissertations. 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 con-

ducted by a committee appointed by the candidate's supervising committee.

DEGREE OF DOCTOR OF PHILOSOPHY

The degree of Doctor of Philosophy (Ph.D.) 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 Ph.D. degree is specifically directed by the division in which he or she has chosen the major subject. Each student should consult with their 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 Ph.D. degree. In some cases, applicants for the Ph.D. may be required to complete requirements for the M.S. degree first; however, this is not a general prerequisite for the Ph.D. Students who have received an Engineer's degree will not be admitted for the Ph.D. degree.

A student who holds a Ph.D. or the equivalent 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 options as specified in this catalog under the section "Special Regulations of Graduate Options." Completion of a minor program of study is recognized on the 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 three academic years (12 terms) of residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for the Ph.D. Of this, at least one year (4 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 their 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 Ph.D. degree for more than six academic years (24 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 thesis adviser, and the option representative.

Registration

Continuity of registration must be maintained until all requirements for the Ph.D. have been completed, with the exception of authorized leaves. Registration is typically required for the term in which the thesis defense is undertaken.

Thesis Advisers and Committee Chairs

The thesis adviser must be a professorial faculty member, defined as professor, associate professor, or assistant professor on a full-time, tenure-track appointment at Caltech. Research faculty and emeritus faculty can supervise research, but the official thesis adviser must be a member of the professorial faculty. Expectations for the relationship between graduate students and faculty advisers are discussed under Guidelines for Graduate Student Advising (page 333).

Progress through the graduate program is monitored in part by the candidacy, thesis advisory, and thesis examination committees detailed in the following sections. Each committee has a chair who is responsible for running the meeting, summarizing the outcome, and working with the graduate student and adviser as appropriate. The chair of each committee is a professorial faculty member distinct from the adviser.

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 Ph.D. and has been in residence at least one term; has initiated a program of study approved by the major option and, if needed, by the minor option; has demonstrated, by written or oral examination, a comprehensive grasp of the major and minor subjects and of subjects fundamental to them; has displayed 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.

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 candidacy committee. A candidacy committee consists of a minimum of three members, two of whom must be professorial faculty. Emeritus faculty, research faculty, JPL staff and external scholars may serve on the candidacy committee, with approval of the option representative and the Dean of Graduate Studies in advance of the candidacy examination. The student should ensure that all members of the committee are available during the examination period and that they are willing to provide timely and appropriate feedback.

A student not admitted to candidacy by the end of the third year or twelfth term of graduate residence at the Institute must petition the Dean of Graduate Studies for permission to register for further work.

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.

Thesis Advisory Committee

Each Ph.D. student is assigned a Thesis Advisory Committee consisting of a minimum of three professorial faculty members. Emeritus faculty, research faculty, JPL staff and external scholars may serve on the thesis examination committee with approval of the option representative and the Dean of Graduate Studies. This committee will meet annually following candidacy, or by the fourth year of graduate study.

Thesis Examination

Each Ph.D. 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 thesis examination, subject to the approval of the Dean of Graduate Studies, may be taken after admission to candidacy whenever the candidate is prepared; however, it must take place at least three weeks before the degree is to be conferred.

The thesis 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 declare their intent to defend by completing the examination notification in Regis not less than two weeks

before the date of the examination. A thesis examination committee consists of four members, with a minimum of three professorial faculty. Emeritus faculty, research faculty, JPL staff and external scholars may serve on the thesis examination committee with approval of the option representative and the Dean of Graduate Studies in advance of the thesis examination.

Thesis

At least two weeks before the final oral examination, the candidate should provide a draft copy of a completed thesis to the Graduate Office for proofreading and to the members of the thesis examination committee. The date of the examination and the composition of the thesis examination committee should be posted in Regis at least two weeks before the final defense is scheduled. In general, registration is required for the term in which the thesis defense is undertaken. 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 a tuition waiver if the student schedules the examination by 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 their thesis during the previous summer or the fall or winter terms; or two weeks before the degree is to be conferred if the candidate defended their thesis during the month of May. It is required that all Ph.D. 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 or the exam composition, see specific graduate options.

Before uploading the final, corrected thesis, it is the candidate's responsibility to obtain approval of the thesis by the option representative and all members of the thesis examination 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 their 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 financial 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. 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 Doctor of Philosophy, at least twelve terms of residence are required, but the necessary study and research typically can be completed in six years or less. 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 30–35. 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 recommended by the option to the Dean of Graduate Studies prior to or in response to the student's petition for admission to candidacy. 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 decision to revoke or withdraw permission to register may be appealed in writing within ten days to the Vice President for Student Affairs or designee.

A Ph.D. 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 Ph.D. student will be allowed to register for more than 24 terms 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 Thesis Advisory Committee chair, and the option representative.

GRADUATE EXPENSES

The tuition and fees charge for all students registering for graduate work is currently $54,537.00 per academic year, payable at the beginning of each term, fall (10/1/2019), winter (1/6/2020), and spring (3/30/2020). 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.

348

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 2019-2020

General:	
Tuition and fees	$54,537.00

Other:	
General Deposit	$100
Books and supplies (approx.)	$1,400.00
Contact Bursar's Office for audit fee.	

Room Catalina apartments:
4 bedroom apt. $655.00 per person per month (plus utilities)
2 bedroom apt. $775.00 per person per month (plus utilities)
1 bedroom apt. $1,315.00 per apt. per month (plus utilities)

Fees are subject to change at the discretion of the Institute.

Fees for Late Payment

A $50.00 late fee penalty may be charged by the Bursar's Office for failure to clear a past-due account at the beginning of instruction.

Fees for Late Registration

Registration is not complete until the student has registered for a program approved by their 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 Dean 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 or coupled 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 www.housing.caltech.edu.

There is one Residential Life Coordinator (RLC) and four 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/partnered graduate students or graduate students with families. Because of limited availability, there is a waiting list for these properties. For additional information and application, go to www.housing.caltech.edu.

Students preferring to live in non-Institute housing typically pay approximately $1,000 to $1,300 per month/each, 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 lunch, 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 for 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 quarters paid monthly throughout the year. Students are also entitled to two weeks of annual vacation and Institute holidays. Students should prearrange their vacation schedule with their adviser. When necessary, graduate assistants may arrange for medical leave, pregnancy leave, bonding leave, or personal leave. 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 be a teaching assistant for a course in which he or she is enrolled. Only teaching assistants with good oral English and who have fulfilled the Institute English proficiency requirement are permitted to teach sections.

All teaching assistants, including undergraduate students with teaching responsibilities, are required to attend teaching-assistant training before payment can be processed. Training sessions are conducted by the Center for Teaching, Learning, and Outreach (CTLO) and occur in the first week of the fall term, typically during orientation, and at least once per term.

Teaching assistants must familiarize themselves with Caltech's policy on harassment (see pages 100–105) and follow other policies related to teaching discussed in the required training. 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
The Institute awards endowed fellowships and scholarships for tuition and/or stipends to graduate students of exceptional ability. Students are also strongly encouraged to apply for scholarships and fellowships from federal and private agencies and organizations to support their graduate studies.

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 200–212). 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

Amori Doctoral Prize in CMS
Established in 2017 by Michael Amori (MS '07), this award honors outstanding dissertations in the computing and mathematical sciences during the current academic year. Awardees are selected by a committee of computing and mathematical sciences faculty each spring.

Tom Apostol Award for Excellence in Teaching in Mathematics
For over fifty years, Tom Apostol has represented great math teach-

ing at Caltech. In 2010 the mathematics option at Caltech set up the Apostol Teaching Awards to recognize excellence in teaching by graduate teachers.

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.

The Bhansali Family Prize in Computer Science

Established in 2001 by Vineer Bhansali (B.S. '87, M.S. '87) in memory of his grandfather, Mag Raj Bhansali, this award. is given 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.

Bhansali Family Dissertation Prize in Computer Science

Established in 2018 by Vineer Bhansali (B.S. '87, M.S. '87) in memory of his grandfather, Mag Raj Bhansali. This prize and honorarium are given to honor outstanding dissertations in computer science, broadly defined, during the current academic year. Awardees are selected by a committee of computer science faculty each spring.

353

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.

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.

Caltech Alumni Association Spirit Award
Commemorating extraordinary activities by Caltech undergraduate students, graduate students, and postdoctoral scholars who best exemplify the spirit, tradition, and values of Caltech, this award is given only when the Alumni Association finds that exceptional activities have occurred that merit this special recognition.

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.

Ben P.C. Chou Doctoral Prize in IST
This prize recognizes outstanding doctoral dissertations in the broad area of information science and technology. The prize was established by Ben P.C. Chou's wife, June, and his son, Scott (B.S. '86), as a lasting tribute to his lifetime dedication to the pursuit of scholarly research and foregoing personal gain in favor of always doing the right thing for society.

Robert F. Christy Prize for an Outstanding Doctoral Thesis in Theoretical Physics

Awarded annually, this prize is given to a student who has produced an outstanding thesis in theoretical physics. Established in 2018, this prize honors the memory of Robert F. Christy, former provost and professor of theoretical physics.

Milton and Francis Clauser Doctoral Prize

An annual prize is awarded to the Ph.D. candidate whose thesis is judged by a committee of the Faculty Board to exhibit significant new work, ingenuity, and originality, and to have the greatest potential to open new avenues of human thought and endeavor. 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 doctorate 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.

France Cordova Graduate Student Fund in Physics

The France Cordova Graduate Student Fund provides resources for one to three graduate students annually to support research-related expenses. The graduate student(s) shall be selected at the discretion of the Division Chair of Physics, Mathematics and Astronomy (PMA). Preference shall be given to student(s) studying broadly in areas in which Professors Gerry Neugebauer, Gordon Garmire and Tom Tombrello made contributions. Each awardee shall be recognized as either a Neugebauer, Garmire, or Tombrello Scholar and the name assigned to each student will be determined by the PMA Division Chair. The fund was established by France Cordova who received her Ph.D in physics from Caltech in 1979.

James A. Cullen Memorial Fellowship Fund

The Cullen Memorial Fellowship is a fund awarded annually to a graduate student or students who have demonstrated outstanding academic achievement in physics. The fellowship was established by the family of Caltech physics alumnus James Cullen (B.S. '46, Ph.D. '56).

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 bioengi-

neering 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-engineering 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 their research field's broader importance; and impact on the scientific community through their 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 their graduate years at the Institute, has made great contributions to graduate life and whose qualities of leadership and responsibility have been outstanding.

David and Barbara Groce Travel Grants in Physics, Mathematics, and Astronomy
The David and Barbara Groce Travel Fund was established by David, BS'58 (Physics), and his wife Barbara to partially pay the travel and meeting costs incurred by PMA graduate students attending and/or presenting research data at scientific meetings or conferences.

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 Graduate Achievement Awards in Mathematics
The Scott Russell Johnson Achievement awards were established in 2001 by Steve and Rosemarie Johnson in memory of Steve's brother Scott who graduated in Math from Caltech in 1983. The Scott Russell Johnson Prize for Excellence in Graduate Study is given to continuing graduate students for extraordinary progress in research and excellence in teaching, or excellent performance as

a first-year graduate student. The Scott Russell Johnson Graduate Dissertation Prize in Mathematics is awarded for the best graduate dissertation in mathematics.

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 Division of Chemistry and Chemical Engineering of the California Institute of Technology making the greatest contribution of the year to the science of chemistry. The selection of the winner of this award shall be made by faculty of CCE and the President of the California Institute of Technology.

Dr. Nagendranath Reddy Biological Sciences Thesis Prize
Awarded to the graduating female Ph.D. candidate in the Division of Biology and Biological Engineering who has produced the most outstanding thesis in the biological sciences for the past year.

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 aeronau-

tics students. In addition, he made many contributions to structural mechanics in areas ranging from aeronautics to the utilization of energy resources.

Dr. Fred Shair Award for Program Diversity
The Dr. Fred Shair Award is given to individuals who stand out as strong supporters of programs that increase the diversity and pluralism in practice at Caltech. Dr. Shair was a member of the chemical engineering faculty, and one of his great accomplishments and contributions to the campus was the creation of the Summer Undergraduate Research Fellowships (SURF) program in 1979. He later included high-achieving students from campuses across the country in an effort to support equity in access to Caltech's research communities.

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.

R. Bruce Stewart Prize
The R. Bruce Stewart Prize for Excellence in Teaching is to be awarded annually to a graduate teaching assistant in physics who demonstrates, in the broadest sense, unusual ability, creativity, and innovation in undergraduate and graduate classroom or laboratory teaching. Named in honor of R. Bruce Stewart, who served as the Founder, Chairman and CEO of Arrowhead Research in Pasadena. Mr. Stewart was a successful entrepreneur who also started and funded over 18 companies in biotechnology, media technology licensing, direct marketing and early internet applications. Throughout his lifetime Mr. Stewart was a great friend to Caltech, supporting and often partnering in the work done by faculty and students. The prize is made possible by memorial gifts made by family and friends of R. Bruce Stewart.

Charles Wilts Prize
The Charles Wilts Prize is awarded annually for outstanding independent research in Electrical Engineering leading to a Ph.D 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.

Women Mentoring Women Candace Rypisi Outstanding Mentor Award

This prize recognizes a woman who has demonstrated a willingness to share their knowledge to enhance the professional and personal development of her mentee(s), provided emotional and moral support and encouragement, enhanced or helped facilitate access to career-related information and exposure to various professional resources, opportunities, networks, and other role models, and promoted the mentee's sense of competence and confidence.

Women Mentoring Women Helen McBride Outstanding Mentee Award

This award recognizes a woman who has demonstrated a sincere desire to succeed as a student, who is committed to her personal development, open and willing to learn from her mentor, and who is receptive to advice and counsel. The recipient will have worked with her mentor to establish realistic goals, and demonstrated a commitment to carrying them out.

Note: Prizes and awards may be subject to federal and state income tax.

SPECIAL REGULATIONS FOR GRADUATE OPTIONS

AEROSPACE (Ae)

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).

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 described in the regulations for the separate degrees listed below, and of electives selected from the list of Aerospace-related courses. This will ensure that the graduating student will be well-qualified for a career in aerospace and related fields.

Examinations, Committees, and Student Responsibilities

To help students achieve satisfactory progress in their 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. The first-year adviser will guide the student in choosing a set of courses appropriate to the students' interests while ensuring the first-year academic requirements (see below) are met.

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 membership as the Candidacy Committee. Students may find further information concerning special option requirements and the requisite option forms on the GALCIT website.

AE Master's Degrees

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 135 units; of these, at least 81 units must be chosen from one of the following curricular tracks:

Aeronautics track
Two 27-unit course sequences chosen from:
- Fluid mechanics (Ae/APh/CE/ME 101 abc)
- Solid/structural mechanics (Ae/AM/CE/ME 102abc)
- Autonomy and control (CDS 131, Ae 103ab), 27 units

Experimental methods (Ae 104abc), 27 units.

Space Engineering track
One 27-unit course sequence chosen from:
- Fluid mechanics (Ae/APh/CE/ME 101abc)
- Solid mechanics (Ae/AM/CE/ME 102abc)

Autonomy and control (CDS 131, Ae 103ab), 27 units
Space engineering (Ae 105abc), 27 units.

Aerospace students in either the Aeronautics or Space Engineering track are required to enroll in a sequence of mathematics courses totaling 27 units appropriate to the student's chosen track and selected in coordination with their first-year advisers. Examples of appropriate courses include ACM/IDS 104, ACM 100ab, ACM 101ab, etc.

Finally, all first-year students are required to enroll in Aerospace Engineering Seminar (3 units Ae 150abc).

A grade of C or higher must be 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 are elective and are to be chosen from courses at Caltech that support the broader goals of the respective programs, subject to the approval of the student's adviser. Students must have a proposed program of courses 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 degree of Doctor of Philosophy (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) for a period of at least two years.

AE 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.

363

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 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.

Research Adviser

Students wishing to pursue studies leading to the Ph.D. must select and be accepted by a research adviser preferably by the end of their third quarter but no later than 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:

Aeronautics track
> Two areas chosen from:
>> Fluid mechanics,
>> Solid/structural mechanics,
>> Autonomy and control.
> Mathematics

Space Engineering track
> One area chosen from:
>> Fluid mechanics,
>> Solid/structural mechanics,
> Autonomy and control
> Mathematics

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 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 135 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 mathematics courses beyond ACM 95/100, and ACM/IDS 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 the advanced seminar 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.

Graduate Information

Minor

No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests or pursue a minor in consultation with their adviser.

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

Prior to graduation, each candidate is required to give a 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 360. A description of the Institute requirements for conferral of a Ph.D. are given on page 343.

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. A 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 École Polytechnique

An educational exchange program is offered by the Aerospace option with École 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 stu-

dents this is equivalent to the requirements for the M.S. 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 master's 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 master's (M2) program at EP. Caltech students must fulfill the requirements of their first-year program and receive their Caltech M.S. diploma prior to proceeding to EP.

Caltech students must register at Caltech during the year spent at École Polytechnique and enroll in the special topics course Ae 240 – Educational exchange at École 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 (ACM)

366

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 homog-

enization 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/IDS 101 ab, ACM 105, CMS/ACM/IDS 107, Ma 108 abc ACM/EE 106 ab, CMS 117, 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 addition, CMS 290 is required for all first year ACM graduate students during each term (fall/winter/spring). 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/IDS 113, ACM 201, 210, ACM/IDS 216, ACM/IDS 217, 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.

ACM 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.

ACM Degree of Doctor of Philosophy

The Preliminary Examination.

Toward the end of the first year, all incoming students must take a preliminary examination administered by the faculty. Its purpose is to ensure a solid and broad knowledge in applied and computational mathematics, and in the event of a deficiency, to direct the students to necessary course and reading.

The Candidacy Examination

To be recommended for candidacy for the Ph.D. degree in Applied and Computational Mathematics, all students must, in addition to meeting the general Institute requirements and passing the preliminary examination, pass a candidacy examination 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 must be taken within the first three years of residence.

Advising and Thesis Supervision

Upon passing the preliminary examination, 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 42.

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.

ACM Subject Minor

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 (AM)

Aims 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. 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 M.S. degree is typically only awarded to students who pursue the Ph.D. degree in applied mechanics at Caltech and who do not already have an M.S. degree in applied mechanics.

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.

AM Preparation for the Graduate Program

Entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering.

While a strong undergraduate program in applied mechanics should provide a suitable preparation, students who have not specialized in applied mechanics as undergraduates may also be admitted for graduate study. For example, 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.

AM Master's Degree

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, which 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 AM subjects listed under the 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). Any course with a number of 100 or greater, may be selected, except that research units may not be included.

    d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

AM Degree of Doctor of Philosophy

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.

371

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 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 applied mechanics is typically completed within the first three years of residency at Caltech.

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.

Required Ph.D. Program

a) *Applied Mechanics Core Subject* (45 units): Course work in core subjects selected from the list below; pass with a grade of at least C:
Ae/APh/CE/ME 101abc, Ae/AM/CE/ME 102abc, AM/CE 151, Ae/Ge/ME 160ab, ME/CE 163, Ae/CE 165ab, ME/CE/Ge 174, CE 181ab, Ae/AM/MS/ME 213ab, Ae/AM/CE/ME 214ab, Ae 220, Ae/CE 221, Ae/AM/ME 223, AM/CE/ME 252, ME/Ge/Ae 266ab.

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.

372

b) *Electives or Minor* (63 units): Additional engineering or science courses with course number 101 or above. Pass with a grade of at least C, courses that are approved by the thesis advisory committee. These courses are intended to provide further depth and incorporate breadth. These units can be used to satisfy a minor requirement in another option.

c) *Advanced mathematics or applied mathematics* (27 units): Pass with a grade of at least C, chosen in consultation with adviser from the following list: ACM 101 or higher, CDS 232, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.

d) *Graduate engineering seminar* (6 units): six terms of AM/CE/ME 150 abc, within twelve terms or, 3 years, in residence at Caltech.

e) *Research* (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

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 adviser: (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.

AM 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 (APh)

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.

APh 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.

APh 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 adviser. 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 adviser 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.

APh 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 adviser. This most often occurs within the first six months of graduate residence. The faculty adviser is the student's primary mentor and the student will work in the adviser'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 adviser 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.

APh 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 toward 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. Students must also complete the degree progress report online upon completion of their courses.

Note: Items in brackets represent optional replacements.

	Total Units
1. Classical Mechanics and Electromagnetism	**27**

Ph 106 a (9 units)

Ph 106 b (9 units)

Ph 106 c (9 units)

2. Quantum Mechanics	**27**

Ph 125 a [Ch 125 a] (9 units)

Ph 125 b [Ch 125 b] (9 units)

Ph 125 c [Ch 125 c] (9 units)

3. Mathematical Methods	**24–27**

ACM/IDS 101 a [Ph 129 a] (12/9 units)

ACM/IDS 101 b [Ph 129 b] (12/9 units)

[Ph 129 c] (9 units)

4. Statistical Physics and Thermodynamics   27

APh/MS 105 a [Ph 127 a or Ae/ME 118 or ChE/
Ch 165] (9 units)

APh/MS 105 b [Ph 127 b or ChE/Ch 164] (9 units)

APh 105 c/MS [Ph 127 c] (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 101 b (9 units)

Ae/APh/CE/ME 101 c (9 units)

Solid-State Physics   27

APh 114 a [Ph 135] (9 units)

APh 114 b [Ph 223 a] (9 units)

APh 114 c [Ph 223 b] (9 units)

Physics of Transport Phenomena in Hydrodynamic Systems   24

APh/Ph 115 (12 units)

APh/Ph/Ae 116 (12 units)

Plasma Physics   27

APh 156 a (9 units)

APh 156 b (9 units)

APh 156 c (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	9

APh 183 (9 units)

Quantum Electronics	27

APh 190 a (9 units)

APh 190 b (9 units)

APh 190 c (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

APh 110 a (2 units)

APh 110 b (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.

Special Regulations

Applied Physics Research

APh 200   27

Students entering the program with advanced preparation may choose either to substitute more advanced courses in the topical areas shown or 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.

APh 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

378

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.

APh 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.

APh Registration Beyond the Sixth Year of Graduate Residence

The annual approval of the student's Thesis Advisory Committee is necessary for registration beyond the twenty-fourth academic term of graduate residence at Caltech.

APh 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 (Ay)

Aims and Scope of the Graduate Program

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 117).

Ay 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. While the Graduate Record Examination scores for verbal and quantitative aptitude tests and the advanced test in physics are not mandatory, they are strongly recommended, especially for the candidates who did not have an adequate opportunity to engage in research as undergraduates, and/or from the countries or institutions where we may not be familiar with the grading systems.

Ay 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.

Ay 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. Suggested courses include, but are not limited to: Ph 101, Ph 105, Ph/Aph 118 a, Ph 127 b, Ph 135, Ph 236, Ph 237. Courses cross-listed with Ay (e.g. Ph/Ay) do not count toward the physics unit requirement, unless specifically allowed by prior consultation between the student, the instructor, and the option representative. Students in radio astronomy may substitute an advanced course in electrical engi-

neering 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. The 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 their third year and above, students are encouraged to take additional advanced astronomy and physics 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 Student Wellness Services.

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.

Ay 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.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS (BMB)

Aims and Scope of the Graduate Program

An integrated approach to graduate study in biochemistry and molecular biophysics has been organized primarily by the Divisions of Biology and Biological Engineering (BBE) and Chemistry and

Chemical Engineering (CCE). The curriculum is designed to provide a broad background in biochemistry and biophysics of macro-molecules and molecular assemblies, in addition to an appropri-ate depth of knowledge in the field selected for the Ph.D. thesis research.

BMB 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. Applicants for admission may submit results from the Graduate Record Examination. 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.

BMB Master's Degree

Students are not admitted to work toward the M.S. degree. An M.S. degree may be awarded only in special circumstances, pro-vided Institute requirements are met, and is typically conferred after the end of the second year of residence.

BMB Degree of Doctor of Philosophy

The Option Representative will counsel and oversee the student's progress upon admission to the graduate program. During the first year of graduate study, students are required to participate in the BMB 202 seminar course. Additionally, as noted below, the option offers a series of courses that 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 spring quarter of the first year. Students are required to take six advanced courses of nine or more units that are appropriate for their particu-lar research interests (as determined by the Option Representative).

Teaching

All students are to serve as teaching assistants for one quarter per year when they are in residence, through the fourth year. In addition to serving an educational purpose, funds for the TA assignments are a component of the stipend. A student may be excused from up to two years of the TA requirement if they obtain funds from a fellowship or obtain research adviser support. Outside factors, such as previous TA positions prior to starting the Ph.D. program, may be considered as satisfying the requirement upon approval by the Option Representative.

Laboratory Rotations

In consultation with the Option Representative and individual pro-

fessors, students will choose three laboratories to do one term research projects during their first year of residence. These laboratory rotations are designed to provide students with an introduction to different areas of biochemistry and molecular biophysics along with identifying a lab for thesis research. It is possible to waive the third rotation by petitioning the Option Representative.

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 proposal in a field outside the student's chosen field of research. A candidacy examination committee of four to five faculty (including the adviser) will be assembled by the student in consultation with their adviser and approved by the Option Representative. The chair of the committee should be identified at this time and should be a member of the Biochemistry and Molecular Biophysics option who is not the thesis adviser. In addition to satisfactory completion of the Candidacy exam, admission to Candidacy requires <u>satisfactory</u> completion of six advanced courses of nine or more units. Upon admission to candidacy, the faculty committee will become the thesis advisory committee. Students are required to meet annually with their thesis advisory committee to evaluate research progress. This committee will also serve as the Ph.D. thesis examination committee. A fifth member may be added at this time. After Candidacy, a student will meet annually with the thesis committee to assess progress.

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 (BE)

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.

BE 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.

BE 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 adviser 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.

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, first term); Reading the Bioengineering Literature (BE 201, second term); Responsible Conduct of Research (Bi 252, third term). A second term of BE 201 is also required for second year graduate students.

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, EE/APh 131, 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 145 ab, ChE/BE 163, BE/CS/CNS/Bi 191ab, ChE 130.

Biology electives: BE 150, Bi/Ch 110, Bi/Ch 111, Bi 114, Bi 115,

Bi 117, Bi 118, Bi 122, Bi/BE 129, Bi 145 ab, BE 153, BE 159, BE/APh 161, Bi/CNS 150.

Math electives: ACM 100 ab, ACM/EE/IDS 116, ACM/ESE 118, AM 125 abc, ChE 105, CDS 110, CDS 140.

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

387

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 Advisory Committee Meetings

Once a student has been admitted to candidacy, each doctoral student will select a Thesis Advisory Committee (TAC). The com-

mittee must be composed of three faculty, plus the adviser(s), including a minimum of two Bioengineering faculty. This committee should meet at least once each year for the remainder of the student's time at Caltech.

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.

BE 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 (Bi)

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.

Bi 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.

Bi Master's Degree

The biology option 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.

Bi 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, devel-

opmental 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 Responsible Conduct of Research (Bi 252), Reading, Writing, Reviewing, Experimental Design and Reproducibility (Bi 253), 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 examination 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 twenty-four terms requires that the student petition the Dean of Graduate Studies for permission to register. 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 com-

mittee 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-Kaiser Permanente School of Medicine MD/PhD Program
There is a dual-degree program between Caltech and the Kaiser Permanente School of Medicine (KPSOM) for the granting of the M.D./Ph.D. degree. Students receive their medical training at KPSOM, and perform their Ph.D. work with any member of the Caltech faculty.

Admission to this dual-degree program is made through the KPSOM M.D./Ph.D. process. The M.D. degree is awarded by KPSOM, and the Ph.D. is awarded by Caltech.

The dual-degree program is directed by Dr. Jose M. Barral, M.D., Ph.D. at KPSOM and Professor Mark Davis at Caltech. For more information, see https://medschool.kp.org/education/curriculum#dual-degrees.

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.

The current directors of the UCLA MSTP are Dr. Carlos Portera-Cailliau and Dr. Siavash Kurdistani, and Caltech professor David Chan is the associate director. For more information, see mstp.healthsciences.ucla.edu.

Caltech-USC MD/PhD 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 co-directors of the USC M.D./Ph.D. program are Drs. Mark Davis and David Hinton. The director for Caltech is Professor Mark Davis. For more information, see http://keck.usc.edu/md-Ph.D.-program/.

Bi 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 (ChE)

Aims and Scope of the Graduate Programs

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, transport phenomena, and materials/energy transformations, 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.

ChE 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.

ChE Master's Degree

Although there is no formal M.S. program in ChE, in the course of their Ph.D. program students may apply for an M.S. degree by submitting an approved thesis and meeting all the other institute requirements for the M.S. program. The thesis must be approved by both the student's adviser and Option Representative.

Course Requirements

At least 135 units of coursework must be completed in order to satisfy the Institute requirements. These units must include ChE 151ab, 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. With advanced permission from the Option Representative, general electives may include courses in the humanities and social sciences. A student must maintain a GPA of ≥ 2.0 to qualify for an M.S. degree. 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.

Research Report

At least three weeks before the degree is to be conferred, a research report on the work performed under ChE 280 must be submitted to both the student's adviser and the Option Representative.

ChE Degree of Doctor of Philosophy

1. Coursework

    a. *Initial Consultation:* Upon arrival at Caltech, the ChE Ph.D. students will meet with the ChE Option Representative to discuss the program, adviser selection, and expectations for the first and second terms. During these two terms, students are expected to take a normal load of three courses per term plus 9 units of research (ChE 280) to cover the rotation (see below). The courses during the first term include one each in advanced Kinetics (ChE 152) and Thermodynamics (ChE 165), and a third course in an area of need or an area that lines up with the research interests of the student. The courses during the second term include one each in advanced Transport (ChE 151 a) and Statistical Thermodynamics (ChE 164) and a third course as above. The third course taken during the first and second terms must be at least 9 units and graded. The entire first year of study will also be discussed.

    b. *Course Requirements:* During the first year, Ph.D. students are required to take the five core courses: ChE 151ab, ChE 152, ChE 164, ChE 165, plus one additional ChE course from the following list: ChE 112, 115, Ch/ChE 140, 147, 148, 155, ChE/ESE 157, 158, 159, ChE/BE 163, 174. The core courses must be graded and a minimum grade of B- is required in each one. There is also a minimum GPA requirement of 2.5 each term of all courses taken. Failure to meet these grade and GPA requirements places the student in a state of deficiency, which may lead to termination of the program if not corrected promptly.

    c. *Subject Minor or External Coursework:* Each student is required to complete either a subject minor or a general program of courses outside chemical engineering. The general program of courses consists of at least 54 units. A maximum of 27 units from the following list of doubly-listed courses can be used by graduate students as part of the 54 unit requirement: ESE/ChE 158; ChE/Ch 140, 147, 148, 155, ESE/Ge/Ch 171. A course in the ACM 100ab sequence will be credited 9 units instead of the nominal 12 units as listed in the catalog. Courses in the Humanities, Arts, and Linguistics are explicitly excluded from the general program. The requirements for a subject minor in other options may be found in the current Caltech Catalog. The general program of courses must be submitted and approved by the Option Representative after the candidacy exam. All courses chosen must be at the graduate level and should constitute an integrated program of study rather than a randomly chosen

collection of courses outside chemical engineering. A grade of C or better is required in any of these courses to remain qualified for the Ph.D. program.

2. Research Adviser

The choice of a research adviser is perhaps the most important decision a graduate student makes during the first year of graduate study. This decision must be made before the end of the second term of the first year, and so it is reasonable to devote significant thought and effort to this task before then.

In the first two weeks of the Fall quarter, all faculty will present overviews of their research program during informal evening sessions. All first-year students must attend all of these sessions. Following these presentations, the students are expected to meet individually with at least two faculty members to discuss proposed research projects and the possibility of doing a rotation in that faculty member's group during the first or second terms. All students must formally join a group by the end of the second term.

3. Rotations

Rotations serve to acquaint the student with a group's research area and style. Two rotations are required, one each during the first and second terms. During a rotation, the student must participate in research activities in the chosen group for at least nine hours per week under the tutelage of a faculty or senior group member. At the end of a rotation, the student must produce a research report and give a group presentation. Afterwards, a rotation completion form must be signed by the rotation adviser and returned to the ChE Option Representative. At the same time, the student and the faculty member must determine whether the "match" of research interests and personalities is good. In the instance of a positive outcome, the student may remain in the same group for a second rotation. Otherwise, the student should proceed to do a second rotation in another group with the same requirements as above. Certain funding agencies (e.g. NIH) require a second rotation in a different group. In that case, the student will be asked to do so, even if she/he desired to remain in a particular group; the student may return to join the first group after completion of the second rotation. All students must find advisers and formally join a group by the end of the second term. Failure to do so terminates the Ph.D. program at Caltech and the student will be asked to leave.

4. Candidacy Exam

All students are required to pass the candidacy examination, ideally before the official start of the second year, or at the latest by

October 15 of the second year. This oral exam is administered by a Candidacy Committee and consists of two parts:

a. A presentation by the student based on the contents of a research progress report.
b. A background questions part broadly related to the research problem presented.

The research progress report must be submitted to the Candidacy Committee members and the ChE Option Representative by August 31st of the first year in residence. The report should expound on the research pursued by the student and is expected to exhibit originality and a professional quality of exposition. It should outline the research problem, the proposed approach, the expected contributions in the general problem area, and the progress of the student at the time of writing. It should also provide clear evidence of the student's understanding of the research topic, the underlying science and technology related to that research, and the student's mastering of the relevant techniques and methodology necessary to pursue the proposed research.

The Candidacy Committee should consist of no fewer than four voting members of the Caltech faculty, with at least three being Chemical Engineering faculty. To ensure the impartiality of the committee, the Chairperson and at least one more of the committee members must have no direct Advisory relationship with the candidate. The choice of the oral exam committee will be made by the student and his/her research adviser and must be approved by the ChE Option Representative. It is the responsibility of the student to obtain approval from each proposed committee member for the date and time of the oral exam. The list of the recommended committee members must be submitted to the Option Representative at the same time as the research progress report.

The second component of the oral exam consists of chemical engineering background questions relating broadly to the student's research topic. The Chairperson of the Candidacy Committee shall be responsible for ensuring that the questions are at an appropriate level, consistent with that of undergraduates at Caltech. For example, if the Ph.D. focus is on heterogeneous catalysis, the student must be able to answer questions on basics such as: surface reaction mechanisms, diffusion/reaction in porous media, and multi-component gas-phase transport, etc. Similar considerations apply to Ph.D. projects related to fluid mechanics, thermodynamics, basic biology, physics, chemistry, etc. The advanced courses taken during the first year should help you prepare well for this part of the exam. Serious gaps in the understanding of classical chemical engineering concepts, approaches, and methodologies applicable to your research may lead to failing the exam even if research progress is deemed adequate. Furthermore, for interdisciplinary projects going beyond classical Chemical Engineering, the student

will be expected to demonstrate good understanding of the fundamentals in other areas directly relevant to their project.

The candidacy exam may have three outcomes: Pass, Conditional Pass, or Fail. Passing the candidacy exam admits the student to Candidacy for the Degree of Doctor of Philosophy. Failing the candidacy exam terminates the student's Ph.D. program at Caltech. When course requirements are met, the student may be awarded an M.S. degree at the recommendation of the Candidacy Committee. Conditional Pass is a special outcome granted only when the student has clearly passed the background questions component, but the committee deems that more is needed on the research front. In this case, the committee chair will put in writing what is required and the time frame to meet those requirements. Under no circumstances is this time to exceed one term. Meeting the stipulated requirements must be reflected in a revised candidacy report, which must be submitted to and approved by the Candidacy Committee by the set deadline. It is at the discretion of the committee to request a re-examination. In any case, a Pass or Fail decision must be reached at the latest by December 15th of the second year in residence. This is a hard deadline for both the student and the committee. If there is no communication to the ChE Option Representative by December 15th, a Fail decision will be entered automatically.

5. Thesis Review Committee

After the student passes the 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 (as a group) during the third 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 fifth 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 at least three months before registration for the next academic year is due. Subsequent registration beyond the fourth 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.

6. Final Thesis and Oral Defense

As a final step in the Ph.D. program, the student is required to submit a satisfactory thesis, present a ChE seminar (open to the general public), and pass a final oral examination.

Procedures for Seminar, Exam, and Committee Selection:
At least three weeks prior to the exam date, the ChE Graduate Records Secretary must be given the title of the seminar, date, time and location. Both the seminar and exam should be scheduled on the same day, with the exam immediately following the seminar. The committee members will be determined by the student and their research adviser, and must be approved by the ChE Option Representative and the Dean of Graduate Studies. The examining committee must include at least four members, of which at least three are voting members of the Caltech faculty and at least two are ChE faculty; one member of the committee may be from off-campus with prior approval of the ChE Option Representative.

7. Graduate Teaching Assignment Duties

All Ph.D. students are required to perform a minimum of 24 term-hours of GTA duties within the ChE Department during their studies. The GTA duties will normally be assigned after the first year in residence. Most students find the teaching assistantship a valuable experience for their future careers. Teaching assistantships outside ChE are permitted but the hours do not count toward the 24-hour TA requirement.

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 (Ch)

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.

Ch 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.

Ch 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 adviser, which courses best serve his or her individual needs. The program of courses must be approved by the research adviser and by the Chemistry Graduate Study Committee.

Ch 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. 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

studies office 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 adviser directing the research and by the chair of the Chemistry Graduate Study Committee.

Ch 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 adviser (or set of co-advisers). Neither students nor faculty can make a commitment to an adviser-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 adviser(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 as a bound, hard-copy document 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.

Graduate Teaching Assignment Duties
All Ph.D. students are required to perform a minimum of one 9 term-hour GTA within the chemistry option before the completion of the fourth year of study. Most students find the teaching assistantship a valuable experience for their future careers.

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 adviser 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.

Typically, a student will provide an updated CV, a short research summary (2-3 pages), and a brief outline of plans for the coming year.

Fourth Year Progress 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. Typically, a student provides an updated CV, a short research summary (2-3 pages), a thesis outline with %-completed for each chapter, and a timeline for completion of the degree. At the meeting, the student will likely present an oral summary of research completed to date as well as an outline of future research plans. Following the discussion, an appropriate timetable for completion of the degree requirements will be discussed and agreed upon. It is also common to discuss plans for post-Caltech at the meeting.

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 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. Two final copies (one on Permalife paper) are to be submitted to the Graduate Office.

Ch 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 (CE)

Aims 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. 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 M.S. degree is typically only awarded to students who pursue the Ph.D. degree in civil engineering at Caltech and who do not already have an M.S. degree in civil engineering.

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.

CE Preparation for the Graduate Program

Entering graduate students are expected to have a thorough back-

ground in undergraduate mathematics, physics, and engineering. While a strong undergraduate program in civil engineering should provide a suitable preparation, students who have not specialized in civil engineering as undergraduates may also be admitted for graduate study. For example, 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.

CE Master's Degree

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, which 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 CE subjects listed under the of the 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 can be included up to a maximum of 27 units.

c) Free electives (27 units). Any course with a number of 100 or greater may be selected, except that research units may not be included.

d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

CE Degree of Doctor of Philosophy

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 graduate school.

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
Civil Engineering Core Subjects (45 units): Course work in core subjects selected from the list below; pass with a grade of at least C: Ae/APh/CE/ME 101abc, Ae/AM/CE/ME 102abc, AM/CE 151, Ae/Ge/ME 160ab, ME/CE 163, Ae/CE165ab, ME/CE/Ge 174, CE 181ab, Ae/AM/MS/ME 213ab, Ae/AM/CE/ME 214ab, Ae 220, Ae/CE 221, Ae/AM/ME 223, AM/CE/ ME 252, ME/Ge/Ae 266ab.

b) *Electives or Minor* (63 units): Additional engineering or science courses with course number 101 or above. Pass with a grade of at least C, courses that are approved by the thesis advisory committee. These courses are intended to provide further depth and incorporate breadth. These units can be used to satisfy a minor requirement in another option.
c) *Advanced mathematics or applied mathematics* (27 units): Pass with a grade of at least C, chosen in consultation with adviser from the following list: ACM 101 or higher, CDS 232, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.
d) *Graduate engineering seminar* (6 units): six terms of AM/CE/ME 150 abc, within twelve terms or 3 years in residence at Caltech.
e) *Research* (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

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 adviser: (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.

CE 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 (CNS)

CNS 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 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.

CNS 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 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/Psy 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/Psy 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 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.

Thesis Advisory Committee

Once admitted to candidacy, the student chooses a Thesis Advisory Committee of at least three faculty. This committee serves as a source of advice independent of the Ph.D. adviser 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 should consist of a minimum of four voting members, three of whom must be Caltech faculty. The final oral examination covers principally the works of the thesis, and according to Institute regulations must be held at least three weeks before the degree is to be conferred.

CNS 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, includ-

ing Bi/CNS/NB/Psy 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 (CSE)

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/EE 106 ab, CMS/ACM/IDS 113, ACM 114 ab, ACM 116, ACM 117, ACM 157, ACM 158, ACM 210 ab, ACM/IDS 216.
- 18 units (two terms) from the following list: CS 115, CS 138 abc, CMS/CS 139 abc, CS 143, CS/IDS 150 ab, CMS/CS/CNS/EE/IDS 155, CS/CNS/EE 156 a, CS 179.
- 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 (CS)

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 Ph.D. program requires a minimum of three academic years of residence; required coursework is generally 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.

CS Master's Degree
There is no terminal M.S. degree in Computer Science. In exceptional circumstances (typically when a student leaves the Ph.D. program without completing the degree), the option representative may approve the awarding of a M.S. degree, if the course requirements have been met and the student has passed the preliminary examination (both are described below).

CS Degree of Doctor of Philosophy
Course requirements

Students must complete a minimum of 135 units of courses numbered 100 or greater, including research units (CS 280). Students should consult with their adviser to ensure balance in the selected courses.

The coursework must include:
- CMS 290 is required for all first year CS graduate students during each term (fall/winter/spring).
- 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, and independent projects. Up to 24 of the 54 units may be taken from non-CS courses from CMS or ACM, including CMS/ACM/IDS 107, CMS/ACM/IDS 113 and CMS 117, or other courses with approval from the option representative.
- 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.

Preliminary examination

Toward the end of the first year, all incoming students must take a preliminary examination administered by the faculty. Its purpose is to ensure a solid and broad knowledge in computer science, and in the event of a deficiency, to direct the students to necessary courses and reading.

Candidacy

To be recommended for candidacy, a student must have completed the required coursework, have passed the preliminary examination, 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 that is approved by the option representative. The chair of the committee must be a Caltech professorial faculty member distinct from the adviser. The examination ascertains the student's breadth and depth of preparation for research in the chosen area. The candidacy 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. The chair of the committee must be a Caltech professorial faculty member distinct from 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 SCIENCE (CMS)

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 Ph.D. 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.

CMS 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.

CMS 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.

415

CMS 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:

Core requirement

Each student will take six core CMS classes, three in applied mathematics (ACM) and three in Computer Science (CS). In both fields, at least two of the three classes will be taken the first year to prepare for the preliminary examination, while the remaining classes will be completed by the end of the student's second year. The core CMS classes are CMS/ACM/IDS 107, CMS/ACM/IDS 113, CMS 117, CMS/CS/IDS 139, CMS/CS/EE/IDS 144, CMS/CS/CNS/IDS 155. These classes must be taken for a grade.

Depth requirement: At least 27 units of courses in one particular subject area will be completed for a grade. The plan for these 27 units must be approved by the CMS option representative.

Breadth requirement: At least 27 units of advanced courses in mathematics, engineering, science, or social science will be completed for a grade. The plan for these 27 units must be approved by the CMS option representative.

Preliminary Examination

All students must pass a preliminary examination on material from two CMS core classes in applied mathematics and two CMS core classes in computer science. The examination is administered by a committee consisting of at least three faculty selected by the CMS option representative. The exam will occur during the student's first year.

Candidacy Examination

All students must pass an oral candidacy examination to ascertain the breadth and depth of preparation for research in the chosen field. The examination will be administered by a committee that consists of at least four faculty, that is approved by the CMS option representative, and that satisfies Institute regulations. In particular, the chair of the candidacy committee must a faculty member distinct from the student's research adviser. The examination will occur during the student's first three years.

CMS 290 is required for all CMS first-year graduate students during each term (fall/winter/spring).

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. After completion of the candidacy exam, each student will form a thesis committee (possibly the same as the candidacy committee) that consists of at least four faculty, that is approved by the CMS option representative, and that satisfies Institute regulations. In particular, the chair of the thesis committee must be a faculty member distinct from the student's research adviser. The thesis committee will meet as needed, but no less than once a year, in order to advise the student.

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 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 (CDS)

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).

CDS 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.

CDS 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: CDS 131, CDS 232, and CDS 231 or CDS 233.
- Complete the following CMS/ACM courses: CMS/ACM/IDS 107, CMS/ACM/IDS 113, or CMS 117.
- Complete an additional 36 units in CDS or other advanced courses in systems theory, dynamical systems, robotics, and/or applied mathematics.
- Complete the focus requirement, consisting of at least 27 units 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 sci-

ence, fluid dynamics, information and communications, net-
working, robotics, and space systems. The program of study
must be approved by the student's counseling committee
and the option representative.
- Preliminary examination. Toward the end of the first year,
all incoming students must take a preliminary examination
administered by the faculty. Its purpose is to ensure a solid
and broad knowledge in control and dynamical systems, and
in the event of a deficiency, to direct the students to neces-
sary courses and reading.
- 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 resi-
dence at the Institute.

In addition, CMS 290 is required for all CDS first year graduate
students during each term (fall/winter/spring).

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 pre-
liminary 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 candi-
dacy 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 candida-
cy 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.

CDS 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 con-
taining 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 (EE)

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.

EE 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 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.

EE 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.

EE 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. In the event that the Adviser is not an EE faculty member, the student should meet with the EE Option Representative and develop an oversight plan to monitor progress. 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. adviser, with at least 54 units of letter-graded EE courses numbered 100 or above (not counting 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 require-

ment. 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.

EE 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 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 (ESE)

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.

ESE 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.

ESE 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.

It is expected that each graduate student will, as part of the Ph.D. graduation requirement, serve as a teaching assistant for one course per year, following completion of the qualifying exam.

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 follow-ing 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.

ESE Subject Minor

Graduate students majoring in another option at the Institute may elect a subject minor in ESE. The ESE minor is intended to sup-plement one of Caltech's graduate degrees and is designed for students who wish to broaden and deepen their expertise with knowledge in ESE. To complete an ESE subject minor, graduate students must enroll in a program of study approved by the ESE option representative, which is to include at least 36 units over two or more terms of graduate-level ESE classes (ESE 100 and above) and 18 units over two or more terms of research under ESE 106 or ESE 300. At least one of the graduate-level ESE classes must be ESE 101, ESE 102, or ESE 103.

424

GEOLOGICAL AND PLANETARY SCIENCES (GPS)

(Geology, Geobiology, Geochemistry, Geophysics, Planetary Science)

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, constitu-tion, 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 under-take 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 environ-mental science and engineering, geobiology, geochemistry, geol-ogy, 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—Not required.
Geochemistry—Subject tests are strongly recommended but not required.
Geology—Not required.
Geophysics—Not required.
Planetary Science—Subject tests are 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 TAC 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.

426

GPS 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 part of a plan of study approved by the option representative, numbered 100 or higher, and part of those used to satisfy the Ph.D. requirement in one of the options of the division. Specifically required are 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).

GPS Degree of Doctor of Philosophy

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.

By the end of the fall term of the second year, students are expected to select a thesis adviser(s) and 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. 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.

Beginning in the second academic year, students are required to serve as teaching assistants for one quarter per year they are in residence.

GPS 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, Ge 125.
> *Chemistry:* Ge/ESE 143, 149, Ge 140 ab, ESE/Ge/Ch 171, 172, ESE/Ch 175, 176.
> *Biology:* ESE/Bi 166, 168, Ge/ESE/Bi 178, 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. Geobiology students must complete one term (6 units) of Ge 109 (Oral Presentation) as an independent study with a faculty member of their choosing, typically the thesis adviser.

Geochemistry

In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geochemistry are required to take one term of Ge 109 in the geochemistry option and 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/min-

eralogy, isotope geochemistry, cosmochemistry, water chemistry/
oceans, atmospheres, biogeochemistry, or advanced chemistry. All
students must have a basic knowledge of chemistry at the level of
Ch 21 and mathematics at the level of Ge 108. If appropriate, 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. With the approval of the geochemistry option rep-
resentative, 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 and students entering with a master's degree
in science or mathematics may be exempt from up to 45 units. In
the oral candidacy exam, the student will be subject to examina-
tion in all four of the chosen subdisciplines.

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 of advanced field geology, in
the form of three terms of Ge 121 abc taken from three different
instructors; (3) 54 additional units in 100- or 200-level science,
math or engineering courses in any field at Caltech. 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 represen-
tative. Courses that cannot be used to satisfy these requirements
include research and reading courses, and certain courses consti-
tuting 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. Geology students are
required to give a 30-minute presentation, including 10 minutes of
discussion, on their research at the Geoclub Seminar series before
admission to candidacy.

429

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 per year from the second
year until the last year prior to obtaining the degree; (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, computa-
tional 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 Ge 108, and higher-level mathematics and physics courses are strongly encouraged. This requirement may be met by previous coursework or through successful completion of this class. All candidates are expected to attend the planetary sciences seminar regularly and register for six terms of Ge 109 (planetary sciences section of oral communication) for a total of 6 units, nominally in the first year and second year. Satisfaction of the oral presentation coursework requirement includes at least one 30-minute presentation by the student in the planetary sciences seminar. Typically, students will present on their research work each year after the first year.

GPS 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 affiliated with the minor will participate in the student's oral thesis defense.

HISTORY (H)

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 (HPS)

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 (MS)

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 broad class of materials such as: physical materials science (solid state physics, quantum mechanics); mechanical materials science (micromechanics, continuum mechanics); soft materials (polymer chemistry/physics, chemical bonding); or oxide materials science (mineralogy/mineral physics). After completing the 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.

MS 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 is also 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.

MS 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 at least 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 137 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 105abc, or ChE/Ch 165 and ChE/Ch 164 and APhMS 105c, or Ae/ME 118 and ChE/Ch 164 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 160ab.

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 121, MS/APh 122, MS 125, MS 142, MS/ME/MedE 116, or APh/MS256.

6. ACM/IDS 104 and ACM 100ab, or ACM/IDS 101ab, or ACM/EE 106ab, or Ph 129ab, or may be waived at the discretion of the student's adviser and option representative.

7. MS 110 (2 units) or APh 110 (4 units).

MS Degree of Doctor of Philosophy

The doctoral program in materials science consists of 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 excellence 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.

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 adviser, 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, offering 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 Core Course requirements 1-7, students must complete a minimum of 137 units of courses, numbered 100 or above, before presenting themselves for Ph.D. candidacy. The coursework towards the Ph.D. degree in materials science is typically completed within the first two years of residency at Caltech.

- All courses must be passed with a grade of at least a C, except for courses taken on a pass/fail basis.
- Students must complete the degree progress report online.
- Alternate Subjects or Areas
    ~ Students entering the program with advanced preparation may choose either to substitute more advanced courses in the topical areas shown or demonstrate competency to the course instructor.
    ~ Students may petition the materials science option representative to accept alternative subjects or areas, but such petitions must be submitted before the student registers for the courses.

b. *Oral Candidacy Examination.* This examination should be taken no later than the end of the student's second year of

residence. The student's research adviser must be on the examining committee, but cannot serve as chair of the committee. The examination is based on the student's research and on coursework, and how it is related to the student's planned research area. The student's research adviser must be on the examining committee, but cannot serve as chair of the committee. The examination is based on the student's coursework, 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 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 third year of graduate residence without successfully completing the candidacy exam.

c. *Research Competence.* The student must have a doctoral research adviser, and must have completed at least 18 units of MS 200. 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.

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. The examining committee must consist of the student's adviser and three members of the Caltech professorial faculty. The chair of the examining committee must be a Caltech professorial faculty member distinct from the adviser. 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.

MS 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 (Ma)

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 163.) Faculty advisers help students plan their programs of study leading to a Ph.D. in mathematics. Entering students are advised by the graduate option representative, who assists them in selecting appropriate courses, depending upon their previous studies.

Ma 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) and at least two terms of discrete mathematics. 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.

Ma Degree of Doctor of Philosophy

Course Program

The graduate courses are listed in section five. The three core course series—Ma 110 abc in analysis, Ma 120 abc in algebra, and Ma 151 abc in geometry and topology—are required of all graduate students. Students are expected to complete each of the core course series during the first year of study, unless they complete the corresponding qualifying exam upon entrance to the program (see section on qualifying exams). 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 considered by the graduate option representative. 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.

Qualifying Examinations

Qualifying examinations in the three core areas—analysis, algebra, and geometry/topology—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 third not taken, students must earn a B or better in all three terms of the corresponding course series. The exams are offered at the beginning of the Fall term and end

of the Spring term each academic year, with exceptional offerings made at other times of the year if needed and approved by the graduate option representative. The examinations must be attempted by the end of the Spring term during the first year of study, and completed by the end of the first academic year. Entering students are permitted to take one or more qualifying examinations at the beginning of the Fall term of their first academic year. If completed successfully, the student may drop the corresponding core course and will be excused from the remainder of the corresponding core requirement. Special exceptions or extensions to the qualifying examination timeline may be considered by the graduate option representative with support from the primary research adviser.

Teaching Requirements

Teaching is an integral part of the Mathematics graduate education. It is expected that students serve as teaching assistants in each term courses are offered unless alternative arrangements have been made with the option and approved by the executive officer.

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 Advising and Tracking Committee

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 formal change of adviser process should be complete by the end of the second academic year.

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 graduate option representative and the executive officer. (See also the section with guidelines for graduate student advising.) In addition to the primary thesis adviser, each student will have a candidacy committee, Thesis Advisory Committee (TAC), and final defense committee. In most cases, the members of all of these committees are the same, but the student has the right to change the members. The student in consultation with his or her adviser will arrange the formation of the committee, which will have at least four members and meet the requirements listed in the subsection Graduate Policies and Procedure entitled 'Degree of Doctor of Philosophy.' At least two of the committee members should be members of the mathematics

professorial faculty and the chair of the committees must be a pro-
fessorial faculty who is not the primary research adviser.

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 qualifying
examinations, core courses, and advanced courses, as well as a
satisfactory oral presentation to a committee of faculty members.
The presentation will describe both the general area of the stu-
dent's proposed thesis research and the specific problem or prob-
lems to be addressed. The candidacy meeting should be complete
by the beginning of the fourth year of study. It normally takes place
during the spring term of the third year. In some cases, during the
summer term of the third year, but scheduling must be done by
the end of the spring term. Special exceptions or extensions to the
admission to candidacy timeline may be considered by the grad-
uate option representative with support from the primary research
adviser.

Thesis Advisory Committee Meetings

The Thesis Advisory Committee (TAC) will track the student's
progress through annual meetings between the candidacy exam
and final defense. It is the responsibility of the student to convene
the TAC during the fourth and fifth year of study. The fourth-year
meeting should take place no later than the end of the winter term
of the fourth year. The fifth-year meeting should take place no later
than the end of the fall term of the fifth year.

Thesis and Final Examination

At least two weeks prior to the final thesis defense, candidates for
the degree of Doctor of Philosophy must deliver copies of their the-
ses to their advisers, to the Graduate Office, and to the members
of the committee 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.

Ma Subject Minor

Students majoring in other fields may take a subject minor in math-
ematics. 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 examina-
tion in the subject minor will be given soon after completion of the
minor program.

Ma Travel Grants

Special funding is available to graduate students to attend conferences and workshops in the United States or abroad (see Bohnenblust and Groce Travel Grants in the 'Prizes' subsection of this section).

MECHANICAL ENGINEERING (ME)

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. 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 M.S. degree is typically only awarded to students who pursue the Ph.D. degree in mechanical engineering at Caltech and who do not already have an M.S. degree in mechanical engineering.

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.

ME Preparation for the Graduate Program

Entering graduate students are expected to have a thorough background in undergraduate mathematics, physics, and engineering. While a strong undergraduate program in mechanical engineering should provide a suitable preparation, students who have not specialized in mechanical engineering as undergraduates may also be admitted for graduate study. For example, 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.

ME Master's Degree

The degree of Master of Science in mechanical engineering is only awarded to students who do not already have a 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,

which 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 ME subjects listed under the 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, MedE, 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). Any course with a number of 100 or greater may be selected, except that research units may not be included.

    d) Graduate Engineering Seminar, AM/CE/ME 150 abc (3 units).

441

ME Degree of Doctor of Philosophy

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.

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.

Required Ph.D. Program

a) *ME Core Subjects* (54 units): Course work in core mechanical engineering subjects selected from the courses below. Pass with a grade of at least C, 36 units must be in a single

track (Depth requirement). An additional 18 units must be from the courses below but can be in any track, including the chosen Depth track.

Tracks:
Thermal-fluid sciences: ME119ab, Aph 115-116, ChE 164-165, ME 118, Phys 127abc, APh 105, ME 120ab, Ae/APh/CE/ME 101abc, ME/CE 163
Mechanics of solids, structures, and materials: Ae/AM/CE/ME 102abc, Ae/APh 104 abc, AM/CE 151, Ae/Ge/ME 160ab, ME/CE 163, Ae 165ab, ME/CE/Ge 174, Ae/AM/MS/ME 213ab, Ae/AM/CE/ME 214ab, Ae 220, Ae/CE 221, Ae/AM/ME 223, AM/CE/ME 252, ME/MS 260, ME/Ge/Ae 266ab

Robotics, Controls and Dynamics: CDS 112, CDS 131, CDS 141, CDS 231, CDS 232, CDS 233. ME/CS/EE 133 ab, CMS/CS/CNS/EE/IDS 155

b) *Electives or Minor* (54 units): Additional engineering or science courses with course number 101 or above. Pass with a grade of at least C, courses that are approved by the thesis advisory committee. These courses are intended to provide further depth and incorporate breadth. These units can be used to satisfy a minor requirement in another option.

c) *Advanced mathematics or applied mathematics* (27 units): Pass with a grade of at least C, chosen in consultation with adviser from the following list: ACM 101 or higher, CDS 232, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above.

d) *Graduate engineering seminar* (6 units): six terms of AM/CE/ME 150 abc, within the twelve terms or 3 years in residence at Caltech.

e) *Research* (54 units). Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

443

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 adviser: (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.

ME 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 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 (MedE)

Aims and Scope of the Graduate Program

The Andrew and Peggy Cherng Department of Medical Engineering offers a program of study that leads to the Ph.D. 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.

MedE Master's Degree

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 Ph.D. degree, provided Institute and Option requirements are met. The Option requirements for the MS degree are the same as those for the Ph.D. 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.

MedE Degree of Doctor of Philosophy

(a) *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 math courses (i.e., 100 level or above) or ACM 100ab, as arranged with his/her adviser. Math courses that are recommended include, but are not limited to: ACM 100ab, ACM/IDS 101, ACM/IDS 104, ACM 105, ACM 106abc, GE/ESE 118, ACM 201ab, ACM 210ab, ACM/EE/CMS 116, AM 125abc, and Ma 112ab.
- Complete the three-term seminar sequence, MedE 100abc (1 unit), with a pass grade.
- Complete MedE 101 (9 units) with a pass grade.
- Complete the two-term core Medical Engineering course sequence, MedE 201ab (18 units).
- Complete MedE/BE/Ae 243 (9 units), ChE/BE/MedE 112 (9 Units) or ChE103B (9 Units).
- Complete EE 111 (9 units).
- Complete at least 27 units of MedE 291 individual research.
- Complete minimally an additional 42 units of advanced courses (100 level or higher) 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 103abc, ChE/BE/MedE 188, EE 112, EE/Ma 126 ab, EE 151, EE/CS/IDS 160, EE/CS 161, MS 115, ME 115 ab, ME 118, ME 119ab.
    2. Solid Mechanics: Ae/AM/CE/ME 102abc, Ae 160, AM/ CE 151ab, MS/ME/MedE 116.
    3. Fluid Mechanics: Ae/APh/CE/ME 101abc, 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, ME/MS 260, MS 115, MS/ME/MedE 116.
    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/APh 180, MedE/EE/BE 168abc, MedE 205.
    7. BioSensing: APh/EE 130, APh/EE 131, APh/EE 132, ChE/BE/MedE 112, EE/MedE 114ab, EE/MedE 115, EE 151, EE 161, MedE/EE/BE 168abc, MedE 202.
    8. Medical Technologies and Devices: APh 109, APh 114abc, APh/EE 130, APh/EE 131, APh/EE 132, BE/EE/

MedE 189 ab, ChE/BE/MedE 112, ChE 115, E/ME/MedE 105 ab, EE 112, EE/MedE 114 ab, EE/MedE 124, EE 151, EE/APh 180, EE/BE/MedE 185, EE/MedE 187, MedE/EE/BE 168abc, MedE 202, MedE 205.

- All required courses must be taken for grades and passed with a grade of at least a C, except for courses offered only on a pass/fail.
- 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 pre-approved 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 research topical 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 second 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. Three members must be Caltech professorial faculty affiliated with Medical Engineering. The fourth member may be a Caltech faculty member or an outside professional of similar standing. The committee must include the adviser, but another member of the committee must be selected as chair. The committee chair must be a Caltech Professorial faculty member. This examination will be a test of the candidate's preparation and knowledge to conduct research in his or her specialized doctoral research area.

(b) *Thesis and Final Examination.* The Ph.D. final thesis defense exam is conducted by a committee that is set up by the student and approved by the option representative. The committee should be made up of minimum of 4 members and at least three of the committee members must be Caltech faculty. The committee must include the adviser, but another member of the committee must be selected as chair. The committee chair must be a Caltech Professorial faculty member. 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.

MedE Subject Minor

A subject minor is not required, but recommended, for the Ph.D. degree in Medical Engineering. However, credits from the subject minor cannot 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 (NB)

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 adviser 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.

NB 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.

NB 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.

NB Degree of Doctor of Philosophy

First-year adviser

Each incoming student is paired with an academic adviser 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 adviser 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. adviser.

Formal Classes
Students take at least 6 quarter courses (54 units) as follows:
1. Bi/CNS/NB 164, Tools of Neurobiology
2. Bi 252, Responsible Conduct of Research
3. One course in molecular, cellular, developmental neurobiology
4. One course in circuits, systems, behavioral biology
5. One course in mathematical methods (depending on the student's background)
6. Two electives

For a list of courses in subject areas 3–5, see the option website. All courses must be taken for a grade unless only offered pass/fail.

Teaching
All students are to serve as teaching assistants for at least 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 30 of the second year, the student must also defend a thesis proposal in an oral exam before a qualifying exam committee of at least three 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 three faculty. This committee serves as a source of advice independent of the Ph.D. adviser 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 should consist of a minimum of four voting members, three of whom must be Caltech faculty. The final oral examination covers principally the work of the thesis, and according to Institute regulations must be held at least three weeks before the degree is to be conferred.

PHYSICS (Ph)

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 information, 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.

449

Admission

The application submission deadline for Physics is December 15. The admission process follows Institute regulations. Applicants are strongly recommended to submit Graduate Record Examination (GRE) scores for the general test and scores for the Advanced Physics subject test.

Ph 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	27 units

(If this course, or its equivalent, was taken as
part of an undergraduate program, it may be
replaced by 27 units of any quantum-mechan-
ics–based course.)

Physics electives	81 units

These must be selected from physics courses
numbered 100 and above.

Other electives	27 units

These must be graduate courses from any
option at Caltech.

   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 con-
current 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 war-
rant normal admission to the physics graduate program.

Ph 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.

Advising structure and thesis supervision

An academic adviser is appointed for each student upon admission
to the graduate program in physics. The academic adviser will serve
as the primary mentor until the student finds a research adviser.
Students will meet with their academic adviser to decide on their
first-year course schedule, and are encouraged to continue these
meetings quarterly until the student finds a research adviser. During
the first year of study, students should consult with their academic
adviser, the option representative, the executive officer, and/or indi-
vidual faculty members to select a tentative research group. Once a
research adviser is selected students may either replace the original-
ly appointed academic adviser or maintain both a research adviser
and academic adviser. At any time, a student may consult with the
option representative concerning such matters as advising.

Students should consult with the executive officer to assemble their oral candidacy committee and Thesis Advisory Committee (TAC) by the end of their third year. The TAC is normally constituted from the candidacy examiners, but students may propose variations or changes at any time to the option representative. The TAC chair is normally someone other than the research adviser. The TAC chair will typically also serve as the thesis defense chair, but changes may be made in consultation with the executive officer for physics and the option representative.

The candidacy committee will examine the student's knowledge of his or her chosen field and will consider the appropriateness and scope of the proposed thesis research during the oral candidacy exam. This exam represents the formal commitment of both student and adviser to a research program. After the oral candidacy exam, students will hold annual meetings with the TAC. The TAC will review the research progress and provide feedback and guidance towards completion of the degree.

The TAC, research, and/or academic advisers 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.

Basic Physics Requirement

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 and proficiency will be tested by two 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. In addition, the class Ph 201 will provide additional problem solving training that matches the basic physics requirement.

The written exams are typically offered in July and in October, and the two 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. The exams can be attempted up to three times and must be successfully completed by the end of the second year of study.

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 graduate courses. The courses must be spread over at least three of the following four areas of advanced physics:

1. Physics of elementary particles and fields
   Nuclear physics, high-energy physics, string theory
2. Quantum information and matter
   Atomic/molecular/optical physics, condensed-matte physics, quantum information
3. Physics of the universe
   Gravitational physics, astrophysics, cosmology
4. Interdisciplinary physics
   e.g., Biophysics, applied physics, chemical physics, mathematical physics, experimental physics

Each area is meant to be covered by the equivalent of a one-term course, and a list of example courses for each of the areas can be found at the physics option website. Other courses may be substituted with permission of the physics option representative.

Oral Candidacy Exam

This exam is primarily a test of the candidate's suitability for research in his or her chosen field. The professor with whom the student plans to do research will be a member of the exam committee, and normally the student will have already begun research (Ph 172) 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. The oral candidacy exam should be completed by the end of the third year (twelve term) of graduate residence.

Admission to Candidacy

To be recommended for Ph.D. candidacy, a student must pass two terms of Physics Seminar (Ph 242), satisfy the Basic Physics Requirement by passing the written candidacy examinations, satisfy the Advanced Physics requirements, and pass the 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.

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 by taking reading and research units (Ph 171–172) in parallel with formal coursework.

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.

Degree progress timeline

The following timeline is required for satisfactory degree progress:

1. Ph 242 should be taken by all students in their first year of graduate study.
2. The written candidacy exams should be attempted by the end of a student's first year of graduate residence, and be passed by the end of the second year.
3. The Advanced Physics requirement should be completed by the end of the second year of graduate residence, but may be extended into the third year depending on the availability of specific courses.
4. The oral candidacy exam must be completed by the end of the third year (twelfth term) of graduate residence.

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.

Ph 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 from physics courses with numbers over 100 must be taken for the subject minor, 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.

QUANTUM SCIENCE AND ENGINEERING (QSE)

Quantum science and engineering (QSE) may be pursued as a subject minor by graduate students who are pursuing Ph.D. degrees in any option. The QSE minor is intended to supplement one of Caltech's graduate degrees and is designed for students who wish to broaden their knowledge of QSE beyond their major

field of study. The QSE minor is also intended to recognize graduate students' interest in and dedication to QSE as demonstrated by the successful completion of a program of study in the field. Completion of the QSE minor program of study will be recognized on the Ph.D. diploma by the statement, "…and by additional studies constituting a minor in Quantum Science and Engineering."

Requirements

To receive the QSE minor, graduate students must fulfill the following requirements:

- 18 units (two terms) from the following list: APh/Ph 138ab
- 18 units (two terms) from the following list: Ph 137ab, Ph/CS 219abc, CS/Ph 120, Ph/APh 223ab, APh 150 (special topics class when topic is relevant to QSE, in consultation with the oversight committee), Ph177 (relevant QSE topic must be chosen in consultation with oversight committee). Other courses relevant to QSE can be included in consultation with the oversight committee.

All courses to be applied toward the QSE minor requirements must be taken on a graded basis, and students must obtain a grade of B- or higher in all courses. At least 18 units of courses that are used to satisfy the QSE minor cannot be used to satisfy course requirements in the major options unless absolutely required by the option. Courses taken as part of the QSE minor are counted toward the total number of units required for the completion of the Ph.D. degree.

QSE Minor Administration

The QSE minor is administered by an oversight committee consisting of faculty members reporting to the chair of the engineering and applied science division. In consultation with their advisers and, if needed, with the QSE 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 QSE. Students must petition the QSE Oversight Committee for approval of their program of study. Upon completion of the program of study, the QSE Oversight Committee will verify that the QSE minor requirements have been fulfilled.

SOCIAL AND DECISION NEUROSCIENCE (SDN)

Aims and Scope of the Graduate Program

The Caltech Ph.D. program in social and decision neuroscience (SDN) prepares students to do research on the neurocomputational basis of decision-making and social interactions. Research in this area requires training in computational modeling, statisti-

cal methods, systems neuroscience, neural measuring methods such as fMRI, EEG or single unit recordings, as well as adequate understanding of related methods and results from the social sciences. Students' career paths include faculty jobs in Neuroscience, Psychology or Marketing; faculty jobs in Economics, Political Science or Finance programs; and industry positions in the technology, data science, finance, and neurotechnology sectors.

SDN Master's Degree

Students are not admitted to work towards the master's degree. The master's degree might be awarded to an SDN student under exceptional circumstances. In order to be eligible for a master's degree, students must complete at least 54 units of the courses required for the Ph.D. with a passing grade, as well as a minimum of 81 additional units of graduate work.

Admission

The program seeks to recruit top students interested in the neurocomputational basis of decision-making and social interactions. Ideal applicants will have very strong quantitative backgrounds, regardless of their undergraduate major. Previous exposure to neuroscience, psychology or economics is useful but not required. Students are required to submit Graduate Record Examination (GRE) verbal and quantitative scores, as well as information regarding their research experience and interests. Students who are not native English speakers are also required to submit evidence of English proficiency, such as the TOEFL, the PTE, or the IELTS.

Course Requirements

Students are required to complete 81 units of graduate coursework related to Social and Decision Neuroscience by the end of their second year, with a grade of B or higher in each class. The coursework must satisfy the following requirements. Students should take a minimum of 54 units during their first year and 27 units during their second year. First year coursework must include CNS/ Psy/Bi 102 ab (Brains, Minds, and Society) and two courses in statistics, econometrics or machine learning. Students are also required to take Bi/CNS/NB/Psy 150 (Introduction to Neuroscience), a graduate course in behavioral economics, and two additional upper-undergraduate or graduate courses (i.e., numbered 100 or higher) in economics, political science or finance.

Lab Rotations

Students are required to complete three quarters of lab rotations during their first year. These rotations should include work in two different labs, for a minimum of one quarter each. Lab rotation plans need to be approved by the option representative by the end of the second week of the Fall quarter. Students must sign-

up for 18 units of CNS 280 (Research in Computation and Neural Systems) or SS 300 (Research in the Social Science) for each quarter of lab rotations. Students are expected to become full members of a research group by the end of the Spring quarter of their first year. The faculty member leading that lab becomes the student's main adviser.

General Knowledge Exam

Students are required to take a written General Knowledge Exam in Social and Decision Neuroscience. The exam is offered during Spring quarter of the second year and students must pass it with a grade of at least 80%. A list of topics and references associated with the exam can be obtained from the option representative.

Other Requirements

Students must satisfy the following additional requirements.

1. They must enroll in Psy 283abc (Graduate Proseminar in Social and Decision Neuroscience) every quarter, from their first to their last quarter in residence. This weekly seminar provides training in academic skills such as writing, presenting, reviewing, and career strategy, as well as breadth of knowledge in Social and Decision Neuroscience.
2. Students must attend four social science seminars in economics, finance or political science every quarter, from their first to their last quarter in residence.
3. Students are also required to complete Bi 252 (Responsible Conduct of Research) during their first year.
4. Students must attend a conference and submit a grant proposal during their second year.
5. Starting their second year, students are expected to TA a minimum of three quarters total during their graduate career.
6. Starting the third year, students must present a poster or give a talk at a conference every academic year.
7. Students must submit yearly progress reports to the SDN option representative by the last day of classes of the Spring quarter, starting on their first year. A template for the report can be obtained from the option representative. These reports will be reviewed by the entire SDN faculty and granted one of three outcomes: approval, conditional approval, or program termination. Students may receive at most one conditional approval of their yearly report during their time in the Ph.D. program.

Candidacy Requirement

Students must form a thesis committee and defend their thesis proposal to the committee. Students must pass this candidacy exam by the last day of classes of their third year. A thesis commit-

tee must have four members subject to the following constraints: at least one should be a neuroscience faculty member, at least one should be a non-neuro social science faculty member, and there should be at most one faculty member from another institution. The main adviser cannot serve as the chair of the thesis committee.

Thesis and Final Examination

The candidate is expected to complete and successfully defend their thesis by the last day of classes of the Spring quarter of their fifth year. Extensions to an additional sixth year will be considered only at the candidacy exam stage and, if necessary, for the proposed research plan.

The time of the defense should be determined in consultation with the main adviser, the thesis committee and, if necessary, the option representative. Students must submit a written copy of their dissertation to the thesis committee at least two weeks prior to the thesis defense date.

SOCIAL SCIENCE (SS)

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.

SS 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 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 the following three-quarter course sequences: Analytical Foundations in Social Science (SS 201abc); Political Theory (SS 202abc); Foundations of Economics (SS 205abc) and Econometrics (SS 222abc). Each class must be completed with a grade of B or better.

At the end of the first year, the faculty will review the overall class performance of each first-year student, and assess the

student's ability for clear self-expression in both oral and written English. A positive assessment of class performance is required for a student to remain in good standing in the program. If class performance is judged unsatisfactory by the faculty, they may terminate the student from the program. In case of language deficiencies, the student is required to take and pass a remedial English class, SS 299, during the summer quarter.

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 the social sciences.
In the fall quarter, all second-year students are required to enroll in SS 224 and at least 27 additional units of advanced Social Science courses. In the winter quarter, all second-year students are required to enroll in at least 36 units of advanced Social Science courses. In the spring quarter, second year students must enroll in at least 27 units of advanced Social Science courses (three typical courses) and enroll in Research in Social Science (SS 300) to work on their second-year paper, for the units remaining to reach 36 units.

Appropriate courses in other options, such as mathematics and computer science, can be substituted for advanced Social Science classes, with the permission of the HSS division's Option Representative. Two classes, SS 281 and SS 300, are taken on a pass/fail basis. All other classes offered for grades must be taken for 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.

Students can tailor their second-year curriculum to their specific research interests, but are expected to include at least two second-year course sequences. Such course sequences include Foundations of Political Economy (SS 210abc), Advanced Economic Theory (SS 211abc), Financial Economics (SS 213abc), Topics in Theoretical and Applied Econometrics (SS 223abc), Applied Empirical Methods in the Social Sciences (SS 228abc), Theoretical and Quantitative Dimensions of Historical Development (SS 229abc), American and Comparative Politics (SS 231abc), and Experimental Methods of Political Economy (SS 260). Students may partially fulfill the second-year sequence requirement by tak-

ing a sequence of courses in mathematics, such as Ma 108abc, Ma 110abc, Ma 144ab, or Ec 181ab.

Third year. Beginning in their third year, and in all subsequent years, all students must enroll in the 3-unit graduate student pro-seminar (SS 282abc) every quarter. Every student must make a presentation in this class at least once a year. Students in the third year may also enroll in additional courses, with the approval of their adviser. Third year students are required to take SS 281 in the fall quarter. In each quarter, third year students should enroll in Research in Social Science (SS 300) for the units remaining to reach 36 units.

Fourth and fifth years. Students need to register for 33 units of SS 300 and 3 units of the graduate student pro-seminar (SS 282abc).

Progress in the program, and advancement to candidacy

In addition to the coursework and examinations described above, students must enroll in at least 36 units every quarter, including summer (SS 300) and complete the following requirements.

By May 1 of the second year, each second-year student must submit an outline describing a planned paper to their paper adviser, their second reader, and the Option Representative. The second-year paper can be co-authored. If the co-author is another graduate student, only one of the students on the joint project can use the paper to fulfill the requirement. The person using the paper for fulfilling the requirement is expected to do most of the actual writing of the paper that is submitted. The final paper is due on September 15. If the paper adviser and the second reader both 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. At the end of the second year, the social science faculty will also meet and assess each second-year student's ability for clear self-expression in both oral and written English. In case of language deficiencies, the student is required to take and pass a remedial English class, SS 299, during the summer quarter. Also, starting their second year, students are expected to TA a minimum of three quarters total during their graduate career.

Third-year students must write a research paper and present it to the faculty at the end of spring quarter. The third-year paper cannot be co-authored, but should be worked on in consultation with and under the direction of the student's primary adviser. The Option Representative will appoint a second third-year paper reader, who must be a member of the Social Sciences professo-

rial faculty. The adviser and second reader will monitor progress and advise the student on the third-year paper. 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 the third year, each student selects a primary adviser. The adviser must be a professorial member of the social science faculty at Caltech. It is possible to change advisers, in consultation with the Option Representative, if a student's research interests change. Students, in consultation with their adviser, must select two additional thesis committee members after the student has advanced to candidacy (normally by the beginning of their fourth year). After a student advances to candidacy, the division chairperson, in consultation with the Option Representative, shall select a fourth member of the committee with an eye to representing the diverse interests of the social science faculty. One of the four members of the thesis committee may be Emeritus faculty, research faculty, or an external scholar, with the approval of the Option Representative and the Dean of Graduate Studies. The chair of the thesis committee must be someone other than the primary adviser, and will be appointed by the Social Science Option Representative in consultation with the primary adviser. The thesis committee will also serve as the examination committee at the thesis defense.

SS 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 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 thesis committee by November 1, and the status communicated by the principal adviser to the Option Representative.

By May 1 of the fourth year, the student is required to convene a

thesis prospectus seminar with their thesis committee. In this seminar, the student is 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. The student and the thesis 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 is completed, the student, in consultation with their adviser, must schedule an oral thesis examination to defend their dissertation. The student must provide a written copy of their dissertation to the Option Representative and all members of the examination committee, and complete the examination notification in Regis, not less than two weeks prior to the thesis examination date. The dissertation is expected to represent publishable, original research.

Courses

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	FS	Freshman Seminars
AN	Anthropology	Ge	Geological and Planetary Sciences
ACM	Applied and Computational Mathematics	H	History
AM	Applied Mechanics	HPS	History and Philosophy of Science
APh	Applied Physics	Hum	Humanities
Art	Art History	IDS	Information and Data Sciences
Ay	Astrophysics		
BMB	Biochemistry and Molecular Biophysics	IST	Information Science and Technology
BE	Bioengineering	ISP	Interdisciplinary Studies Program
Bi	Biology		
BEM	Business, Economics and Management	L	Languages
		Law	Law
ChE	Chemical Engineering	MS	Materials Science
Ch	Chemistry	Ma	Mathematics
CE	Civil Engineering	ME	Mechanical Engineering
CNS	Computation and Neural Systems		
CS	Computer Science	MedE	Medical Engineering
CMS	Computing and Mathematical Sciences	Mu	Music
		NB	Neurobiology
		PVA	Performing and Visual Arts
CDS	Control and Dynamical Systems		
		Pl	Philosophy
Ec	Economics	PE	Physical Education
EE	Electrical Engineering	Ph	Physics
EST	Energy Science and Technology	PS	Political Science
		Psy	Psychology
E	Engineering (General)	SEC	Scientific and Engineering Communication
En	English		
ESL	English As a Second Language		
		SS	Social Science
ESE	Environmental Science and Engineering	SA	Student Activities
		VC	Visual Culture
F	Film	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. Instructors: Austin, Colonius

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 12 abc.* Introduction to continuum mechanics: kinematics, balance laws, constitutive laws with an emphasis on solids. Static and dynamic stress analysis. Two- and three-dimensional theory of stressed elastic solids. Wave propagation. Analysis of rods, plates and shells with applications in a variety of fields. Variational theorems and approximate solutions. Elastic stability. Instructors: Lapusta, Bhattacharya, Pellegrino.

Ae 103 ab. Aerospace Control Systems. *9 units (3-0-6); second and third terms. Prerequisites: CDS 110 (or equivalent), CDS 131 or permission of instructor.* Part a: Optimization-based design of control systems, including optimal control and receding horizon control. Introductory random processes and optimal estimation. Kalman filtering and nonlinear filtering methods for autonomous systems. Part b: Advanced astrodynamics, flight mechanics, and attitude dynamics. Guidance, navigation, and control of autonomous aerospace systems. Instructors: Chung.

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 process-

ing, 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. Space Engineering. *9 units (3-0-6) first term, (2-4-3) second term, (0-8-1) third term; first, second, third terms. Prerequisites: ME 11 abc and ME 12 abc or equivalent.* Part a: Design of space missions based on astrodynamics. Topics include conic orbits with perturbations (J2, drag, and solar radiation pressure), Lambert's Theorem, periodic orbits and ground tracks, invariant manifolds, and the variational equation with mission applications to planetary flybys, constellation, formation flying, and low energy planetary capture and landing. Part b: Introduction to spacecraft systems and subsystems, mission design, rocket mechanics, launch vehicles, and space environments; spacecraft mechanical, structural, and thermal design; communication and power systems; 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 Instructor: Soon-Jo Chung.

CE/Ae/AM 108 ab. Computational Mechanics. *9 units (3-5-1).* 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 2019–20.

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

465

fluid dynamics, solid mechanics, and thermal science applications. Instructor: Dimotakis

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 2019–20.

Ae 121 abc. Space Propulsion. *9 units (3-0-6); first, second, third terms. 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, magneto-plasmadynamic 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: Meiron.

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. Optical Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 2, EE/Ae 157, or equivalent; APh 23 desirable.* This class covers both the fundamentals of optical engineering and the development of space optical systems. Emphasis is on the design and engineering of optical, UV and IR systems for scientific remote sensing and imaging applications. Material covered is: first order optics to find the location, size and orientation of an image; geometrical aberration theory balancing tolerancing optical systems; transmittance, Etendu vignetting; radiative transfer; scalar vector wave propagation—physical optics; scalar diffraction image formation coherence; interferometry for the measurement of optical sur-

faces astronomy; optical metrology wavefront sensing control (A/O); segmented and sparse aperture telescopes; and design topics in coronagraphy, Fourier transform spectrometers, grating spectrometers, and large aperture telescopes. Space optics issues discussed will be segmented sparse aperture telescopes, radiation damage to glass, thermal and UV contamination. Instructor: Breckenridge.

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. Instructors: Lapusta, Ortiz.

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.* 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. Not offered 2019–20.me

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 a. Advanced Fluid Mechanics. *9 units (3-0-6); second term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM/IDS 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. Not offered 2019–20.

Ae 204 ab. Technical Fluid Mechanics. *9 units (3-0-6); second, third terms. 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 2019–20.

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. Not offered 2019–20.

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: McKeon, Chung.

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); first 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. Not offered 2019–20.

Ae/AM/CE/ME 214 ab. Computational Solid Mechanics. *9 units (3-5-1); second, third terms. Prerequisites: ACM 100 ab or equivalent; CE/AM/Ae 108 ab or equivalent or instructor's permission; Ae/ AM/CE/ME 102 abc or Ae/Ge/ME 160 ab or instructor's permission.* Introduction to the use of numerical methods in the solution of solid mechanics and multiscale mechanics problems. First term: Variational principles. Finite element analysis. Variational problems in linear and finite kinematics. Time integration, initial boundary value problems. Elasticity and inelasticity. Constitutive modeling. Error estimation. Accuracy, stability and convergence. Iterative solution methods. Adaptive strategies. Second term: Multiscale modeling strategies. Computational homogenization in linear and finite kinematics. Spectral methods. Atomistic modeling and atomistic-to-continuum coupling techniques. Not offered 2019–20.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6); third 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. Instructor: Ravichandran.

Ae/ME 218. Statistical Mechanics. *9 units (3-0-6); third 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. Instructor: Dimotakis.

Ae 220. Theory of Structures. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE/ME 102 abc.* Fundamentals of buckling and stability, total potential energy and direct equilibrium approaches;

classification of instabilities into snap-through and bifurcations; eigenvalues and eigenvectors of stiffness matrix; Rayleigh-Ritz estimates of buckling loads; buckling of columns; imperfection sensitivity; elastic-plastic buckling; buckling of plates and shells. Selected topics: localization and wrinkling; design of imperfection insensitive shells and other topics. Instructor: Pellegrino.

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 2019–20.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6); winter 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 poly-crystal 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: Andrade.

470

Ae/AM/ME/Ge 225. Special Topics in Solid Mechanics. *Units to be arranged; first, second, third terms.* Subject matter changes depending on staff and student interest.

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. Instructors: Colonius, Meiron.

Ae 233. Hydrodynamic Stability. *9 units (3-0-6); second 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 2019–20.

Ae 234 ab. Hypersonic Aerodynamics. *9 units (3-0-6); second, third terms. 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 hyper-sonic 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 2019–20

Ae 235. Rarefied Gasdynamics. *9 units (3-0-6); first 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 2019–20.

Ae 237 ab. Nonsteady Gasdynamics. *9 units (3-0-6); second, third terms 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 2019–20.

Ae 239 ab. Turbulence. *9 units (3-0-6); second, third terms.* Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM/IDS 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. Not offered 2019–20.

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. Instructors: Meiron, Wincklemans.

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. Not Offered 2019–20.

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 2019–20.

MedE/BE/Ae 243. Physiological Mechanics. *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 2019–20.

Ae 250. Reading and Independent Study. *Units to be arranged; first, second, third terms.* Graded pass/fail only.

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 2019–20.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6); First, second. Prerequisites: Ae/AM/CE/ME 102 abc (concurrently) or equivalent and/or instructor's permission.* Linear elastic fracture mechanics of homogeneous brittle solids (e.g. geo-materials, ceramics, metallic glasses); small scale yielding concepts; experimental methods in fracture, fracture of bi-material interfaces with applications to composites as well as bonded and layered engineering and geological structures; thin-film and micro-electronic components and systems; dynamic fracture mechanics of homogeneous engineering materials; dynamic shear dominated failure of coherent and incoherent interfaces at all length scales; dynamic rupture of frictional interfaces with application to earthquake source mechanics; allowable rupture speeds regimes and connections to earthquake seismology and the generation of Tsunamis. Instructor: Rosakis.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Mechanical Engineering.

ANTHROPOLOGY

An 14. Introduction to Sociocultural Anthropology. *9 units (3-0-6); second 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 15. Human Evolution. *9 units (3-0-6); first term.* What makes humans unique and how did we evolve? This course will review 8 million years of hominin evolutionary history, focusing on the origins of defining features of our species including bipedalism, tool use, language, and advanced cognition. We will examine evidence from primatology and the genetic, fossil, and archaeological records. Concepts from evolutionary biology and anthropology will be covered including adaptation, phylogenetics, life history theory, behavioral ecology, and gene-culture coevolution. Instructor: Alex.

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.

An/PS 127. Corruption. *9 units (3-0-6); second term. Prerequisites: AN 14 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 and ethnic favoritism. How do we measure it? What are its costs and social consequences? What has culture got to do with it? How much does a free press matter? One antidote to corruption is better governance. Students will work closely with the professor to develop an independent and original research project analyzing a large dataset from Kenya. The goal is to understand why some regional governments in Kenya are better able to control this problem than others. Lessons learned should have global implications. 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. Not offered 2019–20.

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. Instructor: Staff.

ACM 80 abc. Undergraduate Thesis. *9 units; first, second, third terms. Prerequisites: 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 ACM faculty (or other faculty as approved by the ACM undergraduate option representative). Projects must include significant design effort. Written report required. Open only to upper class students. Not offered on a pass/fail basis. Instructor: Staff.

ACM 81 abc. Undergraduate Projects in Applied and Computational Mathematics. *Units are assigned in accordance with work accomplished; first, second, third terms. Prerequisites: Consent of supervisor is required before registering.* Supervised research or development in ACM by undergraduates. The topic must be approved by the project supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: Staff.

475

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: Pierce, Meiron.

ACM/IDS 101 ab. Methods of Applied Mathematics. *12 units (4-4-4); first, second terms. Prerequisites: Math 2/102 and ACM 95 ab or equivalent.* 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, generalized eigenfunction expansions, convergence theory. Gibbs and Runge phenomena and their resolution. Chebyshev expansion and Fourier Continuation methods. Review of numerical stability theory for time evolution. Fast spectrally-accurate PDE solvers for linear and nonlinear Partial Differential Equations in general domains. Integral-equations methods for linear partial differential equation in general domains (Laplace, Helmholtz, Schroedinger, Maxwell, Stokes). Homework problems in both 101 a and 101 b include theoretical questions as well as programming implementations of the mathematical and numerical methods studied in class. Instructor: Bruno.

ACM/IDS 104. Applied Linear Algebra. *9 units (3-1-5); first term. Prerequisites: Ma 1 abc, some familiarity with MATLAB, e.g. ACM 11 is desired.* This is an intermediate linear algebra course aimed at a diverse group of students, including junior and senior majors in applied mathematics, sciences and engineering. The focus is on applications. Matrix factorizations play a central role. Topics covered include linear systems, vector spaces and bases, inner products, norms, minimization, the Cholesky factorization, least squares approximation, data fitting, interpolation, orthogonality, the QR factorization, ill-conditioned systems, discrete Fourier series and the fast Fourier transform, eigenvalues and eigenvectors, the spectral theorem, optimization principles for eigenvalues, singular value decomposition, condition number, principal component analysis, the Schur decomposition, methods for computing eigenvalues, non-negative matrices, graphs, networks, random walks, the Perron-Frobenius theorem, PageRank algorithm. Instructor: Zuev.

ACM 105. Applied Real and Functional Analysis. *9 units (3-0-6); second term. Prerequisites: Ma 2, Ma 108a, ACM/IDS 104 or equivalent.* This course is about the fundamental concepts in real and functional analysis that are vital for many topics and applications in mathematics, physics, computing and engineering. The aim of this course is to provide a working knowledge of functional analysis with an eye especially for aspects that lend themselves to applications. The course gives an overview of the interplay between different functional spaces and focuses on the following three key concepts: Hahn-Banach theorem, open mapping and closed graph theorem, uniform boundedness principle. Other core concepts

include: normed linear spaces and behavior of linear maps, completeness, Banach spaces, Hilbert spaces, Lp spaces, duality of normed spaces and dual operators, dense subspaces and approximations, hyperplanes, compactness, weak and weak* convergence. More advanced topics include: spectral theory, compact operators, theory of distributions (generalized functions), Fourier analysis, calculus of variations, Sobolev spaces with applications to PDEs, weak solvability theory of boundary value problems. Instructor: Hoffmann.

ACM/EE 106 ab. Introductory Methods of Computational Mathematics. *12 units (3-0-9); first, second 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. Instructors: Hosseini, Hou.

CMS/ACM/IDS 107. Linear Analysis with Applications. *12 units (3-3-6).* See course description in Computing and Mathematical Sciences.

ACM 109. Mathematical Modelling. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 ab or equivalent.* This course gives an overview of different mathematical tools to analyze partial differential equations encountered across mathematics, biology, engineering and science. We will look at the main properties of different classes of linear and nonlinear PDEs and the behavior of their solutions using tools from functional analysis and calculus of variations with an emphasis on applications. We will discuss different types of reaction-diffusion systems, kinetic equations, advection and transport equations, the method of characteristics, gradient flows and entropy methods, conservation laws, population dynamics, parabolic equations and their spectral analysis, slow-fast dynamics, relaxation, asymptotic stability, blow-up and extinction of solutions, method of moments, instabilities and pattern formation, hydrodynamic scaling techniques and non-dimensionalisation. We will focus on representative models from different areas which may

include: Lotka-Volterra equations, the Fokker-Planck equation, the Boltzmann equation, the Fisher/KPP equation, Burger's equation, movement of cells and bacterial chemotaxis (Patlack-Keller-Segel model), SI models from epidemiology, predator-prey systems, chemical reactions, enzymatic reactions. The list is flexible and depends on the audience. If you are interested in this course, feel free to contact the instructor with (types of) models you would like to study. Instructor: Hoffmann.

Ec/ACM/CS 112. Bayesian Statistics. *9 units (3-0-6).* See course description in Economics.

CMS/ACM/IDS 113. Mathematical Optimization. *12 units (3-0-9).* See course description in Computing and Mathematical Sciences.

ACM/EE/IDS 116. Introduction to Probability Models. *9 units (3-1-5); first term. Prerequisites: Ma 3, some familiarity with MATLAB, e.g. ACM 11 is desired.* This course introduces students to the fundamental concepts, methods, and models of applied probability and stochastic processes. The course is application oriented and focuses on the development of probabilistic thinking and intuitive feel of the subject rather than on a more traditional formal approach based on measure theory. The main goal is to equip science and engineering students with necessary probabilistic tools they can use in future studies and research. Topics covered include sample spaces, events, probabilities of events, discrete and continuous random variables, expectation, variance, correlation, joint and marginal distributions, independence, moment generating functions, law of large numbers, central limit theorem, random vectors and matrices, random graphs, Gaussian vectors, branching, Poisson, and counting processes, general discrete- and continuous-timed processes, auto- and cross-correlation functions, stationary processes, power spectral densities. Instructor: Zuev.

ACM 118. Stochastic Processes and Regression. *12 units (3-0-9); second term. Prerequisites: CMS/ACM/IDS 107 or equivalent, CMS 117 or equivalent, or permission of the instructor.* Stochastic processes: Branching processes, Poisson point processes, Determinantal point processes, Dirichlet processes and Gaussian processes (including the Brownian motion). Regression: Gaussian vectors, spaces, conditioning, processes, fields and measures will be presented with an emphasis on linear regression. Kernel and variational methods in numerical approximation, signal processing and learning will also be covered through their connections with Gaussian process regression Instructor: Owhadi.

AM/ACM 127. Calculus of Variations. *9 units (3-0-6).* For course description, see Applied Mechanics.

Ma/ACM/IDS 140 ab. Probability. *9 units (3-0-6); second, third terms.* For course description, see Mathematics.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6).* For course description, see Mathematics.

ACM/IDS 154. Inverse Problems and Data Assimilation. *9 units (3-0-6); first term. Prerequisites: Basic differential equations, linear algebra, probability and statistics:* ACM/IDS 104, ACM/EE 106 ab, ACM/EE/IDS 116, IDS/ACM/CS 157 or equivalent. Models in applied mathematics often have input parameters that are uncertain; observed data can be used to learn about these parameters and thereby to improve predictive capability. The purpose of the course is to describe the mathematical and algorithmic principles of this area. The topic lies at the intersection of fields including inverse problems, differential equations, machine learning and uncertainty quantification. Applications will be drawn from the physical, biological and data sciences. Instructor: Stuart.

IDS/ACM/CS 157. Statistical Inference. *9 units (3-2-4).* For course description, see Information and Data Sciences.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. *9 units (3-3-3).* For course description, see Information and Data Sciences.

ACM/EE/IDS 170. Mathematics of Signal Processing. *12 units (3-0-9); third term. Prerequisites: ACM/IDS 104, CMS/ACM/IDS 113, and ACM/EE/IDS 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 2019–20.

479

CS/ACM 177 ab. Discrete Differential Geometry: Theory and Applications. *9 units (3-3-3).* For course description, see Computer Science.

ACM 190. Reading and Independent Study. *Units by arrangement.* Graded pass/fail only.

ACM 201. Partial Differential Equations. *12 units (4-0-8); first term. Prerequisites: ACM 95/100 ab, ACM/IDS 101 ab, ACM 11 or equivalent.* This course offers an introduction to the theory of Partial Differential Equations (PDEs) commonly encountered across

mathematics, engineering and science. The goal of the course is to study properties of different classes of linear and nonlinear PDEs (elliptic, parabolic and hyperbolic) and the behavior of their solutions using tools from functional analysis with an emphasis on applications. We will discuss representative models from different areas such as: heat equation, wave equation, advection-reaction-diffusion equation, conservation laws, shocks, predator prey models, Burger's equation, kinetic equations, gradient flows, transport equations, integral equations, Helmholtz and Schrödinger equations and Stoke's flow. In this course you will use analytical tools such as Gauss's theorem, Green's functions, weak solutions, existence and uniqueness theory, Sobolev spaces, well-posedness theory, asymptotic analysis, Fredholm theory, Fourier transforms and spectral theory. More advanced topics include: Perron's method, applications to irrotational flow, elasticity, electrostatics, special solutions, vibrations, Huygens' principle, Eikonal equations, spherical means, retarded potentials, water waves, various approximations, dispersion relations, Maxwell equations, gas dynamics, Riemann problems, single- and double-layer potentials, Navier-Stokes equations, Reynolds number, potential flow, boundary layer theory, subsonic, supersonic and transonic flow. Not offered 2019–20.

ACM/IDS 204. Topics in Linear Algebra and Convexity. *9 units (3-0-6); second term. Prerequisites: ACM/IDS 104 and ACM/EE 106 a, CMS 117, or instructor's permission.* Topic varies by year. 2019–20: Randomized algorithms for linear algebra. This class offers an introduction to the emerging field of randomized algorithms for solving linear algebra problems. Material may include trace estimation, norm estimation, matrix approximation by sampling, random projections, approximating least-squares problems, randomized SVD algorithms, approximate preconditioners, spectral computations, kernel methods, and fast linear system solvers. Assignments will require mathematical proofs, programming, and computer simulation. Instructor: Tropp.

ACM/IDS 213. Topics in Optimization. *9 units (3-0-6); first term. Prerequisites: ACM/IDS 104, CMS/ACM/IDS 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. Instructor: Chandrasekaran.

ACM/IDS 216. Markov Chains, Discrete Stochastic Processes and Applications. *9 units (3-0-6); second term. Prerequisites: ACM/EE/IDS 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/EE/IDS 217. Advanced Topics in Stochastic Analysis. *9 units (3-0-6); second term. Prerequisites: ACM/CMS/EE/IDS 117.* 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 2019–20.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ACM 256. Special Topics in Applied Mathematics. *9 units (3-0-6); first term. Prerequisite: ACM/IDS 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 2019–20.

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 2019–20.

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.

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 (3-5-1).* 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 2019–20.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term; first, second, 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. Dynamics and Vibration. *9 units (3-0-6); first term.* 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 (Eigenvalue 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. Instructor: Asimaki.

AM/ME 165. Finite Elasticity. *9 units (3-0-6); third term. Prerequisites: Ae/Ge/ME 160 a.* Finite theory of elasticity: constitutive theory, semi-inverse methods. Variational methods. Applications to problems of current interest. Not offered 2019–20.

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 ab. Computational Solid Mechanics. *9 units (3-5-1).* 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/Ge 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. *9 units (2-1-6); second term.* The course will cover the basic principles of wave propagation in solid media. It will discuss the fundamental principles used to describe linear and nonlinear wave propagation in continuum and discrete media. Selected recent scientific advancements in the dynamics of periodic media will also be discussed. Students learn the basic principles governing the propagation of waves in discrete and continuum solid media. These methods can be used to engineer materials with predefined properties and to design dynamical systems for a variety of engineering applications (e.g., vibration mitigation, impact absorption and sound insulation). The course will include an experimental component, to test wave phenomena in structured media. Instructor: Daraio.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6).* 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

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. APh/EE 9 ab. Instructor: Scherer. APh/EE 9b not offered 2019-20.

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 2019–20.

APh/EE 23. Demonstration Lectures in Classical and Quantum Photonics. *9 units (3-0-6); second term. Prerequisites: Ph 1 abc.* This course covers fundamentals of photonics with emphasis on modern applications in classical and quantum optics. Classical optical phenomena including interference, dispersion, birefringence, diffraction, laser oscillation, and the applications of these phenomena in optical systems employing multiple-beam interferometry, Fourier-transform image processing, holography, electro-optic modulation, optical detection and heterodyning will be covered. Quantum optical phenomena like single photon emission will be discussed. Examples will be selected from optical communica-

tions, radar, adaptive optical systems, nano-photonic devices and quantum communications. Prior knowledge of quantum mechanics is not required. Instructor: Faraon.

APh/EE 24. Introductory Optics and Photonics Laboratory. *9 units (1-3-5); third term. Prerequisites: APh 23.* Laboratory experiments to acquaint students with the contemporary aspects of optics and photonics 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.Not offered 2019–20.

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 exam. This 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. APh/MS 105ab not offered 2019–20. APh/MS 105c Instructor: 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. Instructors: Troian, 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. Instructor: 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.

486

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. Instructor: Troian.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. *12 units (3-0-9); third 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. Instructor: Troian.

Ph/APh/EE/BE 118 abc. Physics of Measurement. *9 units (3-0-6).* For course description, see Physics.

MS/APh 122. Diffraction, Imaging, and Structure. *9 units (0-4-5); first term.* 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. Not offered 2019–20.

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 nano-structures. Not offered 2019–20.

Ph/APh 137 abc. Atoms and Photons. *9 units (3-0-6).* For course description, see Physics.

APh/Ph 138 ab. Quantum Hardware and Techniques. *9 units (3-0-6); second and third terms. Prerequisites: Ph 125abc or Ph 127abc or Ph137ab or instructor's permission.* This class covers multiple quantum technology platforms and related theoretical techniques, and will provide students with broad knowledge in quantum science and engineering. It will be split into three-week modules covering: applications of near-term quantum computers, superconducting qubits, trapped atoms and ions, topological quantum matter, solid state quantum bits, tensor-product states. APh/Ph 138a will not be offered 2019-20. APh/Ph 138b instructors: Endres, Faraon, Hsieh, Painter

EE/APh 149. Frontiers of Nonlinear Photonics. *9 units (3-0-6).* For course description, see Electrical Engineering.

APh 150. Topics in Applied Physics. *Units and terms to be arranged.* 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.

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: Nadj-Perge.

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. Not offered 2019–20.

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.

489

APh/MS 256. Computational Solid State Physics and Materials Science. *9 units (3-3-3); third term. Prerequisites: Ph125 or equivalent and APh114ab or equivalent.* The course will cover first-principles computational methods to study electronic structure, lattice vibrations, optical properties, and charge and heat transport in materials. Topics include: Theory and practice of Density Functional Theory (DFT) and the total-energy pseudopotential method. DFT calculations of total energy, structure, defects, charge density, bandstructures, density of states, ferroelectricity and magnetism. Lattice vibrations using the finite-difference supercell and Density Functional Perturbation Theory (DFPT) methods. Electron-electron interactions, screening, and the GW method. GW bandstructure

calculations. Optical properties, excitons, and the GW-Bethe Salpeter equation method. Ab initio Boltzmann transport equation (BTE) for electrons and phonons. Computations of heat and charge transport within the BTE framework. If time permits, selected advanced topics will be covered, including methods to treat vander Waals bonds, spin-orbit coupling, correlated materials, and quantum dynamics. Several laboratories will give students direct experience with running first-principles calculations. Not offered 2019–20.

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
(For course descriptions, please see Visual Culture page 735)

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. A field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Hallinan.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. *6 units (2-0-4); second term.* For course description, see Freshman Seminar. Not offered 2019–20.

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. *9 units (3-1-5); 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: Ravi.

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: Steidel.

Ay 30. Introduction to Modern Research. *3 units (2-0-1); first 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: Hillenbrand.

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. Instructors: Howard, Steidel.

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. Prerequisites: 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. During the first term, the student should be fully engaged in and make significant progress on the research project. During second term, the research continues and an outline of the thesis itself should be reviewed with the advisor and the option representative. During third term, the research work is completed and the focus should turn to thesis writing. 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. 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. Instructor: Staff.

Ay 101. Physics of Stars. *9 units (3-0-6); first term. Prerequisites: 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: Fuller.

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: Hillenbrand.

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: Instructor: Kasliwal.

Ay 105. Optical Astronomy Instrumentation Lab. *9 units (1-5-3); third term. Prerequisites: 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 include radiometry measurements, geometrical optics, polarization, optical aberrations, spectroscopy, CCD characterization, vacuum and cryogenic technology, infrared detector technology, adaptive optics (wavefront sensors, deformable mirrors, closed loop control) and a coronography tuturial. Instructor: Mawet.

Ay 111 a. Introduction to Current Astrophysics Research. *3 units; second 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: Kirby.

Ge/Ay 117. Statistics and Data Analysis. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 119. Astroinformatics. *6 units (3-0-3); third term.* This class is an introduction to the data science skills from the applied computer science, statistics, and information technology, that are needed for a modern research in any data-intensive field, but with a special focus on the astronomical applications. Open to graduate and upper-division on undergraduate students in all options. The topics covered include design of data systems, regression techniques, supervised and unsupervised machine learning, databases, Bayesian statistics, high performance computing, software carpentry, deep learning, and visualization. The class will feature real-world examples from cutting-edge projects in which the instructors are involved. Instructors: Djorgovski, Graham, Mahabal.

493

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisite: Ph106bc, 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. Instructor: Phinney.

Ay 122 abc. Astronomical Measurements and Instrumentation. *9 units (3-0-6); first, second terms. Prerequisites: Ph 106bc or equivalent.* Measurement and signal analysis techniques througout the electromagnetic spectrum. Courses may include lab work and

field trips to Caltech observatories. Ay 122a concentrates on infrared, optical, and ultraviolet techniques: telescopes, optics, detectors, photometry, spectroscopy, active/adaptive optics, coronography. Imaging devices and image processing. Ay 122b concentrates on radio through submillimeter techniques: antennae, receivers, mixers, and amplifiers. Interferometers and aperture synthesis arrays. Signal analysis techniques and probability and statistics, as relevant to astronomical measurement. Ay 122c (not offered 2019–20) concentrates on X-ray through gamma-ray techniques. Instructors: Howard, Martin, Hallinan, Ravi.

Ay 123. Structure and Evolution of Stars. *9 units (3-0-6); first 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: Hillenbrand, 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: Hopkins.

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. Instructors: Kasliwal, Kulkarni.

Ay 126. Interstellar and Intergalactic Medium. *9 units (3-0-6); third 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: Kulkarni.

494

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); second 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. Instructors: Hopkins, Martin.

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).* 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. Instructors: Mawet, Kasliwal, Fuller.

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. Astrobiology. *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 astrophysics 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 2019–20.

Ay/Ge 198. Special Topics in the Planetary Sciences. *9 units (3-0-6); third term.* Topic for 2019–20 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: Howard, 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 2019–20.

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term.* Course for graduate students and seniors in astronomy. Topic for 2019–20 will be compact binaries containing white dwarfs, neutron stars and black holes. Formation, mass transfer, accretion, X-ray and pulsar binaries, magnetic and wind interactions, mergers, gravitational waves. Students will be required to lead some discussions; homework will consist exclusively of reading and working through selected papers in preparation for discussions. Instructors: Fuller, Phinney.

Ay 218. Extrasolar Planets. *9 units (3-0-6); third term.* Not offered 2019–20.

496

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 2019–20.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. *9 units (3-2-4).* For course description, see Biology.

Ch/BMB 129. Introduction to Biophotonics. *9 units (3-0-6).* For course description, see Chemistry.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-0-6); first term. Prerequisites: 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. Not offered in 2019–20.

BMB/Bi/Ch 173. Biophysical/Structural Methods. *9 units (3-0-6); second term.* 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, Jensen, and other guest lectures.

BMB/Bi/Ch 174. Advanced Topics in Biochemistry and Biophysics. *6 units (3-0-3); first term; Prerequisites: Bi/Ch 110 or equivalent.* Discussion of research fields in biochemistry and molecular biophysics at Caltech. Instructors: Clemons, Hoelz, Shan and various guest lecturers.

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. *9 units (3-0-6); second 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, and enzyme evolution. 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-steadystate kinetics, kinetic simulations, and kinetics at the single molecule resolution. Instructor: 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,

497

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: 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 Instructor: 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 2019–20.

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 and an overview of the courses offered in the Bioengineering option. Required for BE undergraduates. Graded pass/fail. Instructor: Staff.

Bi/BE 24. Scientific Communication for Biological Scientists and Engineers. *6 units (3-0-3).* 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 co-

advised 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. Not offered 2019–20.

BE/Bi 103 a. Introduction to Data Analysis in the Biological Sciences. *9 units (1-3-5); first term. Prerequisites: Bi 1, Bi 1x, Bi 8, or equivalent; or instructor's permission.* This course covers tools needed to analyze quantitative data in biological systems. Students learn basic programming topics, data organization and wrangling, data display and presentation, basic image processing, and resampling-based statistical inference. Students analyze real data in class and in homework. Instructor: Bois.

BE/Bi 103 b. Statistical Inference in the Biological Sciences. *9 units (1-3-5); second term. Prerequisites: BE/Bi 103 a or equivalent; Ma 1 abc and Ma 3, or Bi/CNS/NB 195, or equivalent; or instructor's permission.* This course introduces students to statistical modeling and inference, primarily taking a Bayesian approach. Topics include generative modeling, parameter estimation, model comparison, hierarchical modeling, Markov chain Monte Carlo, graphical display of inference results, and principled workflows. Other topics may also be included. All techniques are applied to real biological data sets in class and in homework. Instructor: Bois.

BE/Bi 106. Comparative Biomechanics. *9 units (3-0-6); second term.* Have you ever wondered how a penguin swims or why a maple seed spins to the ground? How a flea can jump as high as a kangaroo? If spider silk is really stronger than steel? This class will offer answers to these and other questions related to the physical design of plants and animals. The course will provide a basic introduction to how engineering principles from the fields of solid and fluid mechanics may be applied to the study of biological systems. The course emphasizes the organismal level of complexity, although topics will relate to molecular, cell, and tissue mechanics. The class is explicitly comparative in nature and will not cover medically-related biomechanics. Topics include the physical properties of biological materials, viscoelasticity, muscle mechanics, biological pumps, and animal locomotion. Instructor: Dickinson. Not offered 2019–20.

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. Not offered 2019–20.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6).* For course description, see Chemical Engineering.

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. *9 units (3-2-4).* For course description, see Biology.

Ph/APh/EE/BE 118 abc. Physics of Measurement. *9 units (3-0-6).* For course description, see Physics.

BE 150. Biological Circuit Design. *9 units (3-0-6); third term. Prerequisites: Bi 1, Bi 8, or equivalent; Ma 2, Bi/CNS/NB 195, or equivalent; or instructor's permission.* Quantitative studies of cellular and developmental systems in biology, including the architecture of specific 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. The course will also consider the 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.* P*rerequisites: 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).* 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 95/100 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 2 ab and ACM 95/100 ab, 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: Phillips.

ChE/BE 163. Introduction to Biomolecular Engineering. *12 units (3-0-9).* For course description, see Chemical 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.

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. *9 units (4-0-5).* For course description, see Medical Engineering.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6).* For course description, see Biology.

Bi/BE 182. Animal Development and Genomic Regulatory Network Design. *9 units (3-0-6).* For course description, see Biology.

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. *9 units (3-0-6).* 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).* For course description, see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. *189 a, 12 units (3-6-3) offered both first and third terms. 189b, 9 units (0-9-0) offered only third term. Prerequisites: BE/EE/MedE 189 a must be taken before BE/EE/MedE 189 b.* Part a, students will design and implement computer-controlled biosensing systems, including a pulse monitor, a pulse oximeter, and a real-time polymerase-chain-reaction incubator. Part b is a student-initiated design project requiring instructor's permission for enrollment. Enrollment is limited to 24 students. Instructors: Bois, Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6) second term; (2-4-3) third term. Prerequisites: 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. Not offered 2019–20.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. *12 units; a (3-6-3) second term; b (2-8-2) third term. Prerequisites: none.* 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 self-assembled DNA nanostructures, as well as quantitatively analyze the designs and the experimental data. Students will learn laboratory techniques including fluorescence spectroscopy and atomic force microscopy, and will use software tools and program in MATLAB or Mathematica. Part b is an open-ended design and build project. Enrollment in both parts a and b is limited to 12 students. Instructor: Qian. Not offered 2019–20.

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 201. Reading the Bioengineering Literature. *4 units (1-0-3); second term.* Participants will read, discuss, and critique papers on diverse topics within the bioengineering literature. Offered only for Bioengineering graduate students. Instructor: K. Wang.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units; summer term. 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 summer "boot camp" the week after Commencement, in which students spend all day working on the course. Students who do not have a strong need for the condensed boot camp schedule are encouraged to take BE/Bi 103a instead. Graded pass/fail. Instructor: Bois.

Bi/BE 222. The Structure of the Cytosol. *6 units (2-0-4).* For course description, see Biology.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4).* For course description, see Biology.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. *9 units (3-2-4).* 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. Physiological Mechanics. *9 units (3-0-6).* For course description, see Medical Engineering.

BE 262. Physical Biology Bootcamp. *12 units (2-10-0); summer term. Prerequisites: Enrollment limited to incoming Biology, Biochemistry and Molecular Biophysics, Bioengineering, and Neurobiology graduate students, or instructor's permission.* This course provides an intensive introduction to thinking like a quantitative biologist. Every student will build a microscope from scratch, use a confocal microscope to measure transcription in living fly

embryos and perform a quantitative dissection of gene expression in bacteria. Students will then use Python to write computer code to analyze the results of all of these experiments. No previous experience in coding is presumed, though for those with previous coding experience, advanced projects will be available. In addition to the experimental thrusts, students will use "street fighting mathematics" to perform order of magnitude estimates on problems ranging from how many photons it takes to make a cyanobacterium to the forces that can be applied by cytoskeletal filaments. These modeling efforts will be complemented by the development of physical models of phenomena such as gene expression, phase separation in nuclei, and cytoskeletal polymerization. Graded pass/fail. Instructor: Phillips.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

BIOLOGY

Bi 1. Principles of Biology—The great theories of biology and their influence in the modern world. *9 units (4-0-5); third term.* There are three overarching theories in biology: the theory of the cell, the theory of the gene, and the theory of evolution. Each of them has had major impacts on our lives—for example the concept of the gene has led to treatments for inherited diseases, personalized and genomic medicine, forensic DNA testing, and modern agriculture. Each theory will be discussed from its 19th century origin to its standing in the 21st century, and the scientific understanding and societal impact of each will be sampled. The course will also ask if there is yet a theory of the brain, and if not, how one might be framed. The course is designed to teach what technically adept members of society should know about biology. Instructors: Meyerowitz, Zinn.

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: Regulation of Gene Expression. *9 units (3-0-6); 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. Assignments will include critical dissections of papers from classical and current research literature and problem sets. Instructors: Guttman, Hong.

Bi 9. Cell Biology. *9 units (3-0-6); third term. Prerequisites: Bi 8.* 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: Chan, Prober.

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.

Bi 21. Undergraduate Research with Presentation. *Minimum 12 units per term (0-11-1); first, second, third terms.* Special problems involving laboratory research in biology; to be arranged with instructors before registration. Must give a public presentation reporting results of work. May be counted as advanced lab credit. May be repeated for credit. Instructor: Staff.

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 or biological engineering, 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. Scientific 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 pro-

fessional 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 a 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 selected scientific topics, with feedback from instructors and peers. Fulfills the Institute scientific writing requirement. Instructor: MacLean.

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).* For course description, see Bioengineering.

CNS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/Bi 103 a. Introduction to Data Analysis in the Biological Sciences. *9 units (1-3-5).* For course description, see Bioengineering.

BE/Bi 103 b. Statistical Inference in the Biological Sciences. *9 units (1-3-5).* 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 2019–20.

BE/Bi 106. Comparative Biomechanics. *9 units (3-0-6); second 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, and the intermediary metabolism that provides energy to an organism. Instructor: Clemons.

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 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: Bjorkman, Yui.

507

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. *9 units (3-2-4); third term.* Learn about viruses as fascinating biological machines, focusing on naturally-occurring and evolved variants, in silico viral vector engineering, and computational methods that include structure visualization and machine learning. This course will introduce the fundamentals in the chemistry and biology of viruses, emphasizing their engineerable properties for use in basic research and translational applications. Topics include: viruses by the numbers, mammalian and non-mammalian (plant, bacteria)

viruses, enveloped vs. non-enveloped viruses, host-virus interactions, viral life cycles (replication vs. dormancy), immune responses to viruses, zoonosis, diverse mechanisms of entry and replication, the application of viruses as gene-delivery vehicles (with a focus on adeno-associated viruses or AAVs, lentiviruses, and rabies), and how to engineer viral properties for applications in basic research and gene therapy. The lectures will be complemented by short lab exercises in AAV preparation, bioinformatics and machine learning, and structure visualization. Instructors: Bjorkman, Gradinaru, Van Valen. Given in alternate years; offered 2019–20.

Bi 116. Microbial Genetics. *9 units (3-0-6); second term. Prerequisites: Bi 1, 8, 9 (or equivalent), and ESE/Bi 166.* A course on microbial genetics, emphasizing the history of the discipline as well as modern approaches. Students will be exposed to different ways of manipulating microbial genomes (primarily bacterial, but we will also cover archaea and microbial eukaryotes). The power of microbial genetics to shed light on diverse process will be discussed in a variety of contexts, ranging from environmental science to the mammalian microbiome. Instructors: Mazmanian, Newman. Given in alternate years; offered 2019–20.

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. *9 units (3-0-6); second term. Prerequisites: Bi 8 and Bi 9, or instructor's permission.* Lectures on and 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. Students will choose term project involving writing a grant proposal or quantitative analysis of available datasets relating to lecture topics. Instructor: Stathopoulos. Given in alternate years; not offered 2019–20.

Bi 122. Genetics. *9 units (3-0-6); first term. Prerequisite: Bi 8 or Bi 9, or instructor's permission.* Lecture and discussion course cover-

ing basic principles of genetics. Not open to freshmen. Instructors: Hay, Sternberg, Staff.

Bi/BE 129. The Biology and Treatment 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. The second part will concern newer information on cancer genetics and other topics, taught from the primary research literature. The last part of the course will concern treatments, including chemotherapy, anti-angiogenic therapy, and immunotherapy. Textbook: The Biology of Cancer, 2nd edition, by Robert Weinberg. Instructors: Zinn, Campbell. Given in alternate years; not offered 2019–20.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi 145 a. Tissue and Organ Physiology. *9 units (3-0-6); first term. Prerequisites: Bi 8, 9, Bi/Ch 110. Bi/Ch 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 autonomic nervous system, urinary physiology, and the cardiovascular system. 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, the skeletal system, digestive and hepatic physiology, nutrition, 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.

509

Bi/CNS/NB/Psy 150. Introduction to Neuroscience. *10 units (4-0-6); third term. Prerequisites: Bi 8, 9, or instructor's 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. Letter grades only. Instructors: Adolphs, Lester.

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. *6 units (2-0-4); third term. Prerequisites: Graduate standing or Bi/CNS/NB/Psy 150, or equivalent.* An advanced course of lectures, readings, and student presentations focusing on neural basis of appetites such as hunger and thirst. This course will cover the mechanisms that control appetites both at peripheral and central level. These include genetics, neural manipulation, and viral tracing tools with particular emphasis on the logic of how the body and the brain cooperate to maintain homeostasis. Instructor: Oka. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 154. Principles of Neuroscience. *9 units (3-0-6); first term. Prerequisites: Bi/CNS/NB/Psy 150 or equivalent.* This course aims to distill the fundamental tenets of brain science, unlike the voluminous textbook with a similar title. What are the essential facts and ways of understanding in this discipline? How does neuroscience connect to other parts of life science, physics, and mathematics? Lectures and guided reading will touch on a broad range of phenomena from evolution, development, biophysics, computation, behavior, and psychology. Students will benefit from prior exposure to at least some of these domains. Instructor: Meister. Given in alternate years; not offered 2019–20.

Bi/NB/BE 155. Neuropharmacology. *6 units (3-0-3); second term. Prerequisites: Bi/CNS/NB/Psy 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. Instructor: Lester. Given in alternate years; not offered 2019–20.

510

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. Instructor: Allman. Given in alternate years; not offered 2019–20.

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 2019–20.

Bi 160. Molecular Basis of Animal Evolution. *9 units (3-3-3); third term.* Prerequisites: Bi 8 and/or Bi 9 recommended. We share the planet with well over 1.5 million other animal species. This course covers how the staggering diversity of the animal kingdom came about through underlying molecular evolutionary phenomena, including gene and protein sequence evolution, gene family and genome evolution, the evolution of developmental processes, neural circuit evolution and behavior, and molecular mechanisms that physiologically adapt animals to their environment. Molecular processes involved in speciation will be explained, together with an analysis of constraints and catalysts on the production of selectable variation that have shaped the evolution of animal life. Participants will undertake a laboratory project on evolutionary genomics, involving fieldwork, genome sequencing and comparative genome analysis. The course focuses on the >99.9% of animals that lack backbones. Instructor: Parker.

Pl/CNS/NB/Bi/Psy 161. Consciousness. *9 units (3-0-6).* For course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-4-6); second term. Prerequisites: Bi/CNS/NB/Psy 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 vertebrate and invertebrate brains, using extra- and intracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, electrode fabrication, and data analysis. The class also includes a brain dissection and independent student projects that utilize modern digital neuroscience resources. Instructor: Bremner.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. *6 units (3-0-3); second term.* For course description, see Neurobiology.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6); first term. Prerequisites: Bi/CNS/NB/Psy 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.* The course will serve to introduce graduate students to 1) the process of writing fellowships to train students in preparing effective funding applications; 2) ongoing research projects on campus involving the isolation, culture, and characterization of microbes and microbial communities as well as projects in other fields; and 3) presentation of research and asking questions in research presentations. The first half of the class will involve training in grant writing by drafting an NSF-GRFP proposal. The second half of the class will involve giving chalk talk research presentations. Students can apply from all departments; priority will be given to those in microbiology. Enrollment is limited to instructor approval. Instructor: Hoy.

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).* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 173. Biophysical/Structural Methods. *9 units (3-0-6).* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Advanced Topics in Biochemistry. *6 units (3-0-3).* For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/Psy/NB 176. Cognition. *9 units (4-0-5).* 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 micro-

scopes. 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. Instructor: Collazo. Given in alternate years; not offered 2019–20.

Ge/ESE/Bi 178. Microbial Ecology. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

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/Ch 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. Given in alternate years; offered 2019–20.

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. *9 units (3-0-6); second term. Prerequisites: Bi 8, CS 2, Ma 3; or BE/Bi 103a; 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 data sets. Instructors: Pachter, Thomson.

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. We 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. An important aspect of the course is the lab component in which students design and analyze their own fMRI experiment. Instructor: Tsao. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 185. Large Scale Brain Networks. *6 units (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, not offered 2019–20.

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. Instructor: Wold. Given in alternate years; offered 2019–20.

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. Instructor: Dunphy.

Bi 190. Systems Genetics. *6 units (2-0-4); first 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. Given in alternate years; not offered 2019–20.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6).* 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. Instructor: Goentoro.

Bi/CNS/NB 195. Mathematics in Biology. *9 units (3-0-6); first term. Prerequisites: 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.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units.* For course description, see Bioengineering.

Bi 206. Biochemical and Genetic Methods in Biological Research. *6 units (2-0-4); third term. Prerequisites: graduate standing.* This course will comprise discussions of selected methods in molecular biology and related fields. Instructor: Varshavsky. Given in alternate years; offered 2019–20.

Bi 214. Stem Cells and Hematopoiesis. *9 units (3-0-6); third term. Prerequisites: Graduate standing, or at least one of Bi 114, Bi 117, Bi/Be 182, plus molecular biology.* An advanced course with classes based on active discussion, lectures, and seminar presentations. Development from embryos and development from stem

515

cells are distinct paradigms for understanding and manipulating the emergence of ordered biological complexity from simplicity. This course focuses on the distinguishing features of stem-cell based systems, ranging from the natural physiological stem cells that are responsible for life-long hematopoiesis in vertebrates (hematopoietic stem cells) to the artificial stem cells, ES and iPS cells, that have now been created for experimental manipulation. Key questions will be how the stem cells encode multipotency, how they can enter long-term self-renewal by separating themselves from the developmental clock that controls development of the rest of the organism, and how the self-renewal programs of different stem cell types can be dismantled again to allow differentiation. Does "stemness" have common elements in different systems? The course will also cover the lineage relationships among diverse differentiated cell types emerging from common stem cells, the role of cytokines and cytokine receptors in shaping differentiation output, apoptosis and lineage-specific proliferation, and how differentiation works at the level of gene regulation and regulatory networks. Instructor: Rothenberg.

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 2019–20.

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. Instructor: Allman. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4); second term. Prerequisites: Bi/CNS/NB/Psy 150 or equivalent. Open to advanced (junior or senior) undergraduates only and with instructor permission.* 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 CNS or other graduate 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. Not offered 2019–20.

Bi/BE 222. The Structure of the Cytosol. *6 units (2-0-4); third term. Prerequisites: Bi 9, Bi/Ch 110-111 or graduate standing in a biological discipline.* The cytosol, and fluid spaces within the nucleus, were once envisioned as a concentrated soup of proteins, RNA, and small molecules, all diffusing, mixing freely, and interacting randomly. We now know that proteins in the cytosol frequently undergo only restricted diffusion and become concentrated in specialized portions of the cytosol to carry out particular cellular functions. This course consists of lectures, reading, student presentations, and discussion about newly recognized biochemical mechanisms that confer local structure and reaction specificity within the cytosol, including protein scaffolds and "liquid-liquid phase separations that form "membraneless compartments." Instructor: Kennedy.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4); second term. Prerequisites: Bi/BE 177 or a course in microscopy.* 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. Enrollment is limited. Instructor: Collazo. Given in alternate years; offered 2019–20.

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/Psy 150 or equivalent or instructor's permission.* 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. The class offers weekly hands-on LAB exposure for opsin viral production and delivery to neurons, recording of light-modulated activity, and tissue clearing, imaging, and 3D reconstruction of fluorescent samples. Lecture topics include: opsin design (including natural and artificial sources), delivery (genetic targeting, viral transduction), light activation requirements

(power requirements, wavelength, fiberoptics), 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 of these methods to neuronal circuits (case studies based on recent literature). Instructor: Gradinaru. Given in alternate years; offered 2020-21.

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. Instructors: Aravin, Voorhees.

Bi 250 b. Topics in Systems Biology. *9 units (3-0-6); third term. Prerequisites: Bi 1, Bi 8, or equivalent; Ma 2, Bi/CNS/NB 195, or equivalent; or instructor's permission.* Quantitative studies of cellular and developmental systems in biology, including the architecture of specific 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. The course will also consider the organization of transcriptional and protein-protein interaction networks at the genomic scale. Topics are approached from experimental, theoretical, and computational perspectives. Instructors: Elowitz, Bois.

518

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.

Bi 253. Reading, Writing, Reviewing, Experimental Design and Reproducibility. *6 units (2-0-4); second term.* This course will consider scholarly communication in molecular and cellular biology, broadly defined. Students will learn about data standards, the minimal information required to describe an experiment and computer code. Discussion will include long term storage of data and informatics workflows. Appropriate citation of other article and resources will be considered. We will discuss evaluation of scientific premise, rigorous experimental design and interpretation, appropriate statistical power, authentication of key biological and chemical resources, data and material sharing, record keeping, and transparency in reporting data and observations. Students will learn to read papers critically and practice reviewing short articles from Micropublication: biology, which are short enough to allow a thorough analysis of methods necessary to ensure reproducibility. Graded Pass/Fail. Instructors: Sternberg, Hay, Meister, Staff.

519

Ch/Bi 253. Advanced Topics in Biochemistry. *6 units (2-0-4).* For course description, see Chemistry.

Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Psychology.

CNS/Bi/NB 256. Decision Making. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3); second term.* A project-based course designed to train students to integrate biological, chemical, physical and engineering tools into innovative microbiology research. Students and faculty will brainstorm to identify several "grand challenges" in microbiology. Small teams, comprised of students from different graduate programs and disciplinary backgrounds (e.g. a chemical engineer, a computer scientist and a biologist) and a faculty member, will work to compose a project proposal addressing one of the grand challenges, integrating tools and concepts from across disciplines. Student groups will present draft proposals and receive questions and critiques from other members of the class at check-in points during the academic term. While there will not be an experimental laboratory component, project teams may tour facilities or take field trips to help define the aims and approaches of their projects. At the end of the course, teams will deliver written proposals and presentations that will be critiqued by students and faculty. Instructor: CEMI Faculty.

Bi 270 abc. Special Topics in Biology. *Units to be arranged each term; first, second, third.* 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/Ec/PS 80. Frontiers in Social Sciences. *1 unit (1-0-0); first term.* Weekly seminar by a member of the Caltech Social Sciences faculty to discuss a topic of their current research or teaching at an introductory level. The course can be used to learn more about different areas of study and about undergraduate courses within the Social Sciences. The course will also be useful to those interested in pursuing the BEM, EC or PS options, or participating in research (SURF, for example) under supervision of the Social Science faculty. Graded pass/fail. Instructor: Cvitanic.

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 determined by instructor. Instructors: Staff, visiting lecturers.

BEM 102. Introduction to Accounting. *9 units (3-0-6); third term.* This course provides the knowledge and skills necessary for the student to understand financial statements and financial records and to make use of the information for management and investment decisions. Topics include: an overview of financial statements and business decisions; the balance sheet, the income statement, and the cash flow statement; sales revenue, receivables, and cash; cost of goods sold and inventory; long-lived assets and depreciation, and amortization; current and long-term liabilities; owners' equity; investments in other corporations and an introduction to financial statement analysis. Instructor: Ewens.

BEM 103. Introduction to Finance. *9 units (3-0-6); second term. Prerequisites: Ec 11 required; Ma 1 abc recommended (to be familiar with calculus and linear algebra).* Finance, or financial economics, covers two main areas: asset pricing and corporate finance. For asset pricing, a field that studies how investors value securities and make investment decisions, we will discuss topics like prices, risk, and return, portfolio choice, CAPM, market efficiency and bubbles, interest rates and bonds, and futures and options. For corporate finance, a field that studies how firms make financing decisions, we will discuss topics like security issuance, capital structure, and firm investment decisions (the net present value approach, and mergers and acquisitions). In addition, if time permits, we will cover some topics in behavioral finance and household finance such as limits to arbitrage and investor behavior. Instructor: Jin.

BEM 104. Investments. *9 units (3-0-6); third 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: Roll.

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. Since 2015, the course is offered in the flipped format: the students are required to watch lectures online, while problem solving and case and paper presentations are done in class. Instructor: Cvitanic.

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. Not offered 2019–20.

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. Not offered 2019–20.

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. Instructor: Ewens.

BEM 111. Quantitative Risk and Portfolio Management. *9 units (3-0-6); second 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 112. International Financial Markets. *9 units (3-0-6); second term. Prerequisites: BEM 103 or instructor permission.* The course offers an introduction to international financial markets, their comparative behavior, and their inter-relations. The principal focus will be on assets traded in liquid markets: currencies, equities, bonds, swaps, and other derivatives. Attention will be devoted to (1) institutional arrangements, taxation, and regulation, (2) international arbitrage and parity conditions, (3) valuation, (4) international diversification and portfolio management, (5) derivative instruments, (6) hedging, (7) dynamic investment strategies, (8) other topics of particular current relevance and importance. Not offered 2019–20.

BEM 117. 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/ESE 119. Environmental Economics. *9 units (3-0-6); first term. Prerequisites: 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). Instructor: Ledyard.

523

BEM/Ec 150. Business Analytics. *9 units (3-0-6); first 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. Not offered 2019–20.

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 units (1-4-4); first term. Prerequisites: Ma 2 (may be taken concurrently).* Introduction to the solution of engineering problems through the use of the computer. Elementary programming in Python 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); second term. Prerequisites: ChE 15 and Ma 2.* 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. 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: Gavalas, Ismagilov.

ChE 70. Special Topics in Chemical Engineering. *Units by arrangement; terms to be arranged; offered by announcement. Prerequisites: instructor's permission.* Special problems or courses arranged to meet the emerging needs of undergraduate students. May be repeated for credit, as content may vary. Grading scheme at instructor's discretion. Instructors: to be determined.

ChE 80. Undergraduate Research. *Units by arrangement, instructor's permission required.* Research in chemical engineering offered as an elective in any term. Graded pass/fail. Instructor: Staff.

ChE 90 abc. 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. In addition, students must submit a midterm progress report in each term, end-of-term progress reports at the end of the first two terms, and a thesis draft in the third term. A grade will not be assigned prior to completion of the thesis, which normally takes three terms. A P grade will be given for the first two terms 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: Davis.

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, Flagan.

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.

525

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. NMR characterization methods in the areas of heterogeneous catalysts, batteries, energy storage materials, etc. will be reviewed. More specific topics include NMR methods in solid state such as magic angle spinning (MAS), cross-polarization (CP), NMR of quadrupole nuclei, multiple pulse and multi-dimensional solid state NMR experiments, dynamics NMR. Hands-on experience will be provided via separate laboratory sessions using solid NMR spectrometers at Caltech Solid State NMR facility. Instructor: Hwang.

ChE 115. Electronic Materials Processing. *9 units (3-0-6); third term.* P*rerequisites: 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 2019–20.

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 abc, 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. Instructor: Vicic.

ChE 128. Chemical Engineering Design Laboratory. *9 units (1-6-2); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, or instructor's permission.* Short-term, open-ended research projects targeting chemical processes in microreactors. Projects include synthesis of chemical products or nanomaterials, 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. Students will propose and execute research projects in biomolecular engineering and synthetic biology. Emphasis will be on projects that apply rational or library-based design strategies to the control of system behavior. Instructors: Davis, Vicic.

527

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6).* For course description, see Chemistry.

ChE 141. Data Science for Chemical Systems. *9 units (1-2-6); second term. Prerequisites: ChE 15, ACM/IDS 104.* Through short lectures, in-class activities, and problem sets, students learn and use methods in data science to complete projects focused on

(i) descriptive and predictive analyses of chemical processes and (ii) Quantitative Structure Property Relationships (QSPR). Topics covered may include six sigma; SPC & SQC; time-series analysis; data preprocessing; dimensionality reduction; supervised, reinforcement, and unsupervised learning; decision tree & clustering methods; univariate and multivariate regression; and visualization. Python is the programming language of instruction. Instructor: Vicic.

ChE 142. Challenges in Data Science for Chemical Systems. *9 units (1-0-8); third term. Prerequisites: ChE 141.* Student groups complete a one-term, data-science project that addresses an instructor-approved chemical engineering challenge. The project may be an original research idea; related to work by a research group at the Institute; an entry in a relevant national/regional contest; a response to an industry relationship; or other meaningful opportunity. There is no lecture, but students participate in weekly progress updates. A student may not select a project too similar to research completed to fulfill requirements for ChE 80 or ChE 90abc. Instructor: Vicic.

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 the structure and dynamics of polymeric liquids, 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, a chain under different solvent conditions; dilute and semi-dilute solutions; thermodynamics of polymer blends and block copolymers; polyelectrolytes; rubber elasticity; polymer gels; linear viscoelasticity of polymer solutions and melts. Instructor: Wang. Not offered 2019–20.

ChE 151 ab. Physical and Chemical Rate Processes. *12 units (3-0-9); second, third 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. Prerequisites: ChE 101 or instructor's permission.* Survey of heterogeneous reactions on metal and oxide catalysts. Langmuir-Hinshelwood versus Eley-Rideal reaction

mechanisms. Reaction, diffusion, and heat transfer in heterogeneous catalytic systems. Characterization of porous catalysts. Instructor: Giapis.

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 2019–20.

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 8, 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 (Python is the language of instruction). 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. Instructor: Wang.

529

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); first 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 and active matter. Other topics may be discussed depending on class needs and interests. Instructor: Brady.

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. Not offered 2019–20.

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. Instructor: Staff.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

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.

Courses

CHEMISTRY

Ch 1 ab. General Chemistry. *6 units; 9 units; a (3-0-3) first term; b (4-0-5) second term.* Lectures and recitations dealing with the principles of chemistry. First term: Chemical bonding—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 dynamics—spectroscopy, thermodynamics, kinetics, chemical equilibria, electrochemistry, and introduction to organic chemistry. Graded pass/fail. Instructors: Lewis (a), Robb, Miller (b).

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. Freshmen who enter in academic years 2017, 2018, and 2019 must take Ch 3 a in their first nine terms of residence in order to be graded pass/fail. Freshmen entering in academic year 2020 and thereafter must take Ch 3 a in their first six terms of residence in order to be 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, photochemistry, and photoelectrochemistry, culminating in the construction and testing of dyesensitized solar cells. Freshmen who enter in academic years 2017, 2018, and 2019 must take Ch 3x in their first nine terms of residence in order to be graded pass/fail. Freshmen entering in academic year 2020 and thereafter must take Ch 3x in their first six terms of residence in order to be graded pass/fail. 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 organome-

tallic 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 organome-tallic complexes (Ch 5 b) will be included. Methodology will include advanced techniques of synthesis and instrumental characteriza-tion. Terms may be taken independently. Instructors: Grubbs (a), Agapie (b). Part b not offered 2019–20.

Ch 6 ab. Physical and Biophysical Chemistry Laboratory. *9 units (1-5-3); second, third terms. Prerequisites:* Ch 1, Ch 4 ab, and Ch 21 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. Part b not of-fered 2019–20. Instructor: Okumura.

Ch 7. Advanced Experimental Methods in Bioorganic Chemistry. *9 units (1-6-2); third 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 commer-cially available enzymes for useful synthetic organic transformations will be illustrated. Instructor: Hsieh-Wilson.

Ch 8. Experimental Procedures of Synthetic Chemistry for Premedical Students. *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.* Open to non-pre-medical students, as space allows. Introduction to methods of extraction, synthesis, separation and purification, and spectroscopic characterization of Aspirin, Tylenol, and medical test strips. Instructor: Mendez.

Ch/ChE 9. Chemical Synthesis and Characterization for Chemi-cal 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 organometallic compounds. Specific emphasis will be focused on following the scientific method in the study of model organic and inorganic materials. Enrollment priority given to chemical engineering majors. Instructor: Mendez.

Ch 10 abc. Frontiers in Chemistry. *1 unit (1-0-0) first, second terms; 6 units (1-4-1) third term. Prerequisites: Open for credit to freshmen and sophomores. 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. 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. *9 units (3-0-6); second term.* This course will cover acid-base equilibria, complex ion formation, chelation, oxidation-reduction reactions, and partitioning equilibria. These topics will serve as the basis for introducing separation techniques such as gas and liquid chromatography and the hyphenated techniques associated with them (GC-MS, LC-MS, etc.) Laboratory activities will be integrated with the course topics. Instructor: Rees.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); third term. Prerequisites: Ch 1 ab, Ch 3 a or Ch 3 x, Ch 14, 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. Instructor: Dalleska.

533

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, chemical dynamics, statistical mechanics, and thermodynamics. Instructors: Chan (a), Wei (b), Beauchamp (c).

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 recommended.* Develops the basic principles of solution thermodynamics, transport processes, and reaction kinet-

ics, with emphasis on biochemical and biophysical applications. Instructor: Not offered 2019–20.

Ch 41 abc. Organic Chemistry. *9 units (4-0-5); first, second, third terms. Prerequisites: Ch 1 ab or instructor's permission.* The synthesis, structure, and mechanisms of reactions of organic compounds. Instructors: Grubbs (a), Hsieh-Wilson (b), Reisman (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. Senior Thesis Research. *9 units; first, second, third terms. Prerequisites: Instructor's permission.* Three terms of Ch 82 are to be completed during the junior and/or senior year of study. 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. An oral thesis defense will be arranged by the CUSC in the third term for all enrollees. The first two terms of Ch 82 will be taken on a pass/fail basis, and the third term will carry a letter grade. Instructors: Okumura, staff.

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. Class size limited to 12 students. Instructor: Bikle.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1); first, second, third terms.* Training in the writing of scientific research papers for chemists and chemical engineers. Fulfills the Institute scientific writing requirement. Instructors: Parker, Weitekamp.

Ch 101. Chemistry Tutorials. *3 units (1-0-2); third term.* Small group study and discussion on special areas of chemistry, chemical engineering, molecular biology, or biophysics. Instructors drawn from advanced graduate students and postdoctoral staff will lead weekly tutorial sessions and assign short homework assignments,

readings, or discussions. Tutorials to be arranged with instructors before registration. Instructors: Staff.

Ch 102. Introduction to Inorganic Chemistry. *9 units (4-0-5); third term. Prerequisites: Ch 41 ab.* Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, organometallic, biological inorganic chemistry, and solid-state chemistry. Instructors: Hadt, See.

Ch 104. Intermediate Organic Chemistry. *9 units (4-0-5); second term. Prerequisites: Ch 41 abc.* A survey of selected topics beyond introductory organic chemistry, including reaction mechanisms and catalysis. Instructor: Fu.

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. Prerequisites: Ch 102 or instructor's permission.* Introduction to group theory, ligand field theory, and bonding in coordination complexes and organotransition metal compounds. Systematics of bonding, reactivity, and spectroscopy of commonly encountered classes of transition metal compounds. Instructors: Agapie, Hadt.

Ch 117. Introduction to Electrochemistry. *9 units (3-0-6); first term.* Discussion of the fundamentals and applications of electrochemistry with an emphasis on the structure of electrode-electrolyte interfaces, the mechanism by which charge is transferred across it, experimental techniques used to study electrode reactions, and application of electrochemical techniques to study materials chemistry. Topics may vary but usually include diffusion, cyclic voltammetry, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Instructor: See.

535

Ch 120 ab. Nature of the Chemical Bond. *Ch 120 a: 9 units (3-0-6), third term; Ch 120 b: (1-1-7), first 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) third term. Prerequisites: Ch 21 a or Ch 125 a.* Application of Atomistic-based methods [Quantum Mechanics (QM) and Molecular Dynamics (MD)] for predicting the structures and properties of molecules and solids and simulating the dynamical properties. This course emphasizes hands-on use of modern commercial software (such as Jaguar for QM, VASP for periodic QM, and LAMMPS for MD) for practical applications and is aimed at experimentalists and theorists interested in understanding structures, properties, and dynamics in such areas as biological systems (proteins, DNA, carbohydrates, lipids); polymers (crystals, amorphous systems, co-polymers); semi-conductors (group IV, III-V, surfaces, defects); inorganic systems (ceramics, zeolites, superconductors, and metals); organo-metallics, and catalysis (heterogeneous, homogeneous, and electrocatalysis). Ch121a covers the basic methods with hands-on applications to systems of interest using modern software. The homework for the first 5 weeks emphasizes computer based solutions. For the second 5 weeks of the homework each student proposes a short research project and uses atomistic simulations to solve it. Ch121b 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 125 abc. The Elements of Quantum Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 21 abc or an equivalent brief introduction to quantum mechanics.* A treatment of quantum mechanics with application to molecular and material systems. The basic elements of quantum mechanics, the electronic structure of atoms and molecules, the interactions of radiation fields and matter, and time dependent techniques relevant to spectroscopy will be covered. The course sequence prepares students for Ch 225 and 226. Instructors: Cushing (a), Weitekamp (b), part (c) not offered 2019–20.

Ch 126. Molecular Spectra and Molecular Structure. *9 units (3-0-6); third term. Prerequisites: Ch 21 and Ch 125 a/Ph 125 a 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, density matrixies, linear and nonlinear interactions of radiation and matter. Instructor: Blake. Not offered 2019–20.

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.* For course description, see Geological and Planetary Sciences.

Ch/BMB 129. Introduction to Biophotonics. *9 units (3-0-6); first term. Prerequisites: Ch 21abc required. Ch 125, 126 recommended.* This course will cover basic optics and introduce modern optical spectroscopy principles and microscopy techniques. Topics include molecular spectroscopy; linear and nonlinear florescence microscopy; Raman spectroscopy; coherent microscopy; single-molecule spectroscopy; and super-resolution imaging. Instructor: Wei. Not offered 2019–20.

Ch 135. Chemical Dynamics. *9 units (3-0-6); third 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. Not offered 2019–20.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6); second term. 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. Instructor: Lewis (b), part a Not offered 2019–20.

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.) Not offered 2019–20.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); first term. Prerequisites: Ch 41 abc; Ch 21 abc recommended.* An advanced survey of selected topics in modern organic chemistry. Topics vary from year to year and may include structural and theoretical organic chemistry; materials chemistry; macromolecular chemistry; mechanochemistry; molecular recognition/supramolecular chemistry; reaction mechanisms; reactive intermediates; pericyclic reactions; and photochemistry. Not offered 2019–20.

Ch 145. Chemical Biology of Proteins. *9 units (3-0-6); first term. Prerequisites: Ch 41 abc; Bi/Ch 110 recommended.* An advanced survey of current and classic topics in chemical biology. Content draws largely from current literature and varies from year-to-year. Topics may include the structure, function, and synthesis of peptides and proteins; enzyme catalysis and inhibition; cellular metabolism; chemical genetics; proteomics; posttranslational modifications; chemical tools to study cellular dynamics; and enzyme evolution. Instructor: Ondrus.

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 2019–20.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6), first 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: Robb.

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 first three weeks of the term. Graded pass/fail. Instructors: Fu, Stoltz, Ondrus.

Ch 153 abc. Advanced Inorganic Chemistry. *9 units (3-0-6); second (Ch 153 a), third (Ch 153 c offered in 2019–20, alternating with Ch 153 b in subsequent years) 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 to the characterization of inorganic and bioinorganic species, with an emphasis on the practical application of Moessbauer, EPR, and pulse EPR spectroscopies. Ch 153 c: Theoretical and spectroscopic approaches to understanding the electronic structure of transition metal ions. Topics in the 153bc alternate sequence may include saturation magnetization and zero-field splitting in magnetic circular dichroism and molecular magnetism, hyperfine interactions in electron paramagnetic resonance spectroscopy, Moessbauer and magnetic Moessbauer spectroscopy, vibronic interactions in electronic absorption and resonance Raman spectroscopy, and bonding analyses using x-ray absorption and/or emission spectroscopies. Instructors: Gray, Winkler (a), Hadt/Peters (c).

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, Agapie (a), part b Not offered 2019–20.

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.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-0-6).* 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 term.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Advanced Topics in Biochemistry. *6 units (3-0-3).* For course description, see Biochemistry and Molecular Biophysics.

ESE/Ch 175. Physical Chemistry of Engineered Waters. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ch 176. Physical Organic Chemistry of Natural Waters. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. *9 units (3-0-6).* 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. Not offered 2019–20.

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. Instructor: Gray.

Ch 225. Advanced Quantum Chemistry. *9 units (3-0-6); second term. Prerequisites: Ch125ab or equivalent, or permission of instruc-*

tors. The electronic structure of atoms and molecules, the interactions of radiation fields and matter, scattering theory, and reaction rate theory Instructor: Chan/Miller.

Ch 226. Optical and Nonlinear Spectroscopy. *9 units (3-0-6); third term. Prerequisites: Ch125ab, or equivalent instruction in quantum mechanics.* Quantum mechanical foundations of optical spectroscopy as applied to chemical and material systems. Topics include optical properties of materials, nonlinear and quantum optics, and multidimensional spectroscopy. Instructors: Blake, Cushing.

BMB/Ch 230. Macromolecular Structure Determination with Modern X-ray Crystallography Methods. *12 units (2-4-6).* For course description, see Biochemistry and Molecular Biophysics.

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. Instructors: Stoltz (a), Reisman, Virgil (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 2019–20.

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: Stoltz, Reeves.

Ch 251. Advanced Topics in Chemical Biology. *9 units (3-0-6); second term. Prerequisites: or 146 or consent of the instructor.* Advanced Topics in Chemical Biology. Hours and units to be arranged. Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Ch 252. Advanced Topics in Chemical Physics. *Hours and units to be arranged.* Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Ch/Bi 253. Advanced Topics in Biochemistry. *6 units (2-0-4); third term.* Hours and units to be arranged. Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

Ch 279. Rotations in Chemistry. *Variable units as arranged with the advising faculty member; first, second, third terms.* By arrangement with members of the faculty, properly qualified graduate students will have the opportunity to engage in a short-term research project culminating in a presentation to their peers enrolled in the course and participating laboratories. (Pass-Fail only).

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 Analysis 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 2019–20.

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 (3-5-1); first, second terms. Prerequisites: 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 2019–20.

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. Not offered 2019–20.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term.* For course description, see Applied Mechanics.

AM/CE 151. Dynamics and Vibration. *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 inter-action), and seismic design requirements for reinforced concrete structures. Not offered 2019–20.

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 Struc-tures. *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. Not offered 2019–20.

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 genera-tion of forces and measurement of structural response. Not offered 2019–20.

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 build-ings, seismic sources, earthquake size scaling, earthquake hazard calculations, rupture dynamics. Not offered 2019–20.

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 ab. Computational Solid Mechanics. *9 units 3-5-1.* 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 2019–20.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. *9 units (2-1-6).* For course description, see Applied Mechanics.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6).* For course description, see Aerospace.

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: Siapas.

545

CNS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6); second, third terms. Prerequisites: Bi/CNS/NB/Psy 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. Part a: Reinforcement learning. Unconscious and conscious processing. Emotion. Behavioral economics. Goal-directed and habit learning. Facial processing in social neuroscience. Part b: History and mechanisms of reinforcement. Associative learning. Mentalizing and strategic thinking. Neural basis of prosociality. Exploration-exploitation trad-

eoff. Functions of basal ganglia. Instructors: O'Doherty/Adolphs, Camerer.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5).* For course description, see Psychology.

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. Instructor: O'Doherty. Not offered 2019–20.

Psy/CNS 132. Computational Reinforcement-learning in Biological and Non-biological Systems. *9 units (3-0-6).* For course description, see Psychology.

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/Psy 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. *6 units (2-0-4); spring.* For course description, see Biology.

Bi/CNS/NB 154. Principles of Neuroscience. *9 units (3-0-6).* For course description, see Biology.

CMS/CS/CNS/EE/IDS 155. Machine Learning & Data Mining. *12 units (3-3-6).* For course description, see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-1-5).* For course description, see Computer Science.

Bi/CNS/NB 157. Comparative Nervous Systems. *9 units (2-3-4).* For course description, see Biology.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6).* For course description, see Biology.

CS/CNS/EE/IDS 159. Advanced Topics in Machine Learning. *9 units (3-0-6).* For course description, see Computer Science.

Pl/CNS/NB/Bi/Psy 161. Consciousness. *9 units (3-0-6).* For course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-4-6).* For course description, see Biology.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. *6 units (3-0-3); second term.* For course description, see Neurobiology.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6); second term.* For course description, see Biology.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. *12 units (3-3-6).* For course description, see Computer Science.

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/Psy/NB 176. Cognition. *9 units (4-0-5); 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. Instructor: Shimojo. Given in alternate years; Not Offered 2019–20.

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 units (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. Instructors: Meister, Perona, Shimojo, Tsao. Given in alternate years; Offered 2019–20.

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. Not Offered 2019–20.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6).* For course description, see Bioengineering.

Bi/CNS/NB 195. Mathematics in Biology. *9 units (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/Psy 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. Not Offered 2019–20.

Bi/CNS 250 c. Topics in Systems Neuroscience. *9 units (3-0-6).* For course description, see Biology.

CNS 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. Not Offered 2019–20.

Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Psychology.

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. Instructor: Andersen.

CNS 280. Research in Computation and Neural Systems. *Hours and units by arrangement.* For graduate students admitted to candidacy in computation and neural systems.

Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0).* For course description, see Psychology.

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 (3-5-1); 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 fundamental algorithms; algorithm design principles, in particular recursion and dynamic programming; 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 projects 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. Instructor: Blank.

CS 3. Introduction to Software Design. *9 units (1-6-2); third term. Prerequisites: CS 2 or equivalent.* CS 3 is a practical introduction to designing large programs in a low-level language. Heavy emphasis is placed on documentation, testing, and software architecture. Students will work in teams in two 5-week long projects. In the first half of the course, teams will focus on testing and extensibility. In the second half of the course, teams will use POSIX APIs, as well as their own code from the first five weeks, to develop a large software deliverable. Software engineering topics covered include code reviews, testing and testability, code readability, API design, refactoring, and documentation. Instructor: Blank.

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 6/106 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 students to research areas in CS through weekly overview talks by Caltech faculty and aimed at first-year undergraduates. More senior students may wish to take the course to gain an understanding of the scope of research in computer science. Graded pass/fail. Instructor: Low.

EE/CS 10 ab. Introduction to Digital Logic and Embedded Systems. *6 units (2-3-1).* For course description, see Electrical Engineering.

CS 11. Computer Language Lab. *3 units (0-3-0); first, second, third terms. Prerequisites: 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. This course is available for undergraduate students only. Graduate students should register for CS 111. CS 11 may be repeated for credit of up to a total of nine units. Instructors: Blank, Pinkston, Vanier.

551

CS 19 ab. Introduction to Computer Science in Industry. *2 units (1-0-1); first, second terms.* This course will introduce students to CS in industry through weekly overview talks by alums and engineers in industry. It is aimed at second-year undergraduates. Others may wish to take the course to gain an understanding of the scope

of computer science in industry. Additionally students will complete short weekly assignments aimed at preparing them for interactions with industry. This course is closed to first and second term freshman for credit. Graded pass/fail. Instructor: Ralph.

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); first term. Prerequisites: Familiarity with C equivalent to having taken the CS 11 C track or CS 3.* 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: Blank.

CS 37. Algorithms in the Real World. *9 units (2-6-1); first term. Prerequisites: CS 2, CS 24, Ma 6 or permission from instructor.* This course introduces algorithms in the context of their usage in the real world. The course covers compression, advanced data structures, numerical algorithms, cryptography, computer algebra, and parallelism. The goal of the course is for students to see how to use theoretical algorithms in real-world contexts, focusing both on correctness and the nitty-gritty details and optimizations. Implementations focus on two orthogonal avenues: speed (for which C is used) and algorithmic thinking (for which Python is used). Not offered 2019–20.

CS 38. Algorithms. *9 units (3-0-6); third term. Prerequisites: CS 2; Ma/CS 6 a or Ma 121 a; and CS 21.* 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.

CS 42. Computer Science Education in K-14 Settings. *6 units (2-2-2); first, second, third terms.* This course will focus on computer science education in K-14 settings. Students will gain an understanding of the current state of computer science education within the United States, develop curricula targeted at students

from diverse backgrounds, and gain hands on teaching experience. Through readings from educational psychology and neuropsychology, students will become familiar with various pedagogical methods and theories of learning, while applying these in practice as part of a teaching group partnered with a local school or community college. Each week students are expected to spend about 2 hours teaching, 2 hours developing curricula, and 2 hours on readings and individual exercises. Pass/Fail only. May not be repeated. Instructor: Ralph.

EE/CS 53. Microprocessor Project Laboratory. *12 units (0-12-0).* For course description, see Electrical Engineering.

CS/EE/ME 75 abc. 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 and third terms; units according to project selected.* 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. Instructor: Burdick.

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: Faculty.

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: Faculty.

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: Faculty.

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.

HPS/PI/CS 110. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

CS 111. Graduate Programming Practicum. *3 units (0-3-0); first, second, third terms. Prerequisites: CS 1 or equivalent.* 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. This course is available for graduate students only. Undergraduates should register for CS 11. Instructors: Blank, Pinkston, Vanier.

554

Ec/ACM/CS 112. Bayesian Statistics. *9 units (3-0-6).* For course description, see Economics.

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 languag-

es. 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: Joshi.

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 2019–20.

EE/CS 119 abc. Advanced Digital Systems Design. *9 units (3-3-3).* For course description, see Electrical Engineering.

CS/Ph 120. Quantum Cryptography. *9 units (3-0-6); first term. Prerequisites: Ma 1b, Ph 2b or Ph 12b, CS 21, CS 38 or equivalent recommended (or instructor's permission).* This course is an introduction to quantum cryptography: how to use quantum effects, such as quantum entanglement and uncertainty, to implement cryptographic tasks with levels of security that are impossible to achieve classically. The course covers the fundamental ideas of quantum information that form the basis for quantum cryptography, such as entanglement and quantifying quantum knowledge. We will introduce the security definition for quantum key distribution and see protocols and proofs of security for this task. We will also discuss the basics of device-independent quantum cryptography as well as other cryptographic tasks and protocols, such as bit commitment or position-based cryptography. Instructor: Vidick.

CS/IDS 121. 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: Murray.

CS 122. Database System Implementation. *9 units (3-3-3); second term. Prerequisites: CS 2, CS 38, CS/IDS 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 2019–20.

CS 123. Projects in Database Systems. *9 units (0-0-9); third term. Prerequisites: CS/IDS 121 and CS 122.* Students are expected to execute a substantial project in databases, write up a report describing their work, and make a presentation. Not offered 2019–20.

CS 124. Operating Systems. *12 units (3-6-3); third 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/CS/MedE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0).* For course description, see Electrical Engineering.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 3.* For course description, see Electrical Engineering.

EE/Ma/CS/IDS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

ME/CS/EE 129. Experimental Robotics. *9 units (3-6-0).* For course description, see Mechanical Engineering.

CS 131. Programming Languages. *9 units (3-0-6); third term. Prerequisites: CS 4.* CS 131 is a course on programming languages and their implementation. It teaches students how to program in a number of simplified languages representing the major programming paradigms in use today (imperative, object-oriented, and functional). It will also teach students how to build and modify the implementations of these languages. Emphasis will not be on syntax or parsing but on the essential differences in these languages and their implementations. Both dynamically-typed and statically-typed languages will be implemented. Relevant theory will be covered as needed. Implementations will mostly be interpreters, but some features of compilers will be covered if time permits. Enrollment limited to 20 students. Instructor: Vanier.

ME/CS/EE 133 abc. Robotics. *9 units (3-3-3).* For course description, see Mechanical Engineering.

ME/CS/EE 134. Robotic Systems. *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.

EE/Ma/CS/IDS 136. Topics in Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS 138. Computer Algorithms. *9 units (3-0-6); third term.* This course is identical to CS 38. Only graduate students for whom this is the first algorithms course are allowed to register for CS 138. See the CS 38 entry for prerequisites and course description. Instructor: Schulman.

CMS/CS/IDS 139. Analysis and Design of Algorithms. *12 units (3-0-9).* For course description, see Computation and Mathematical Sciences.

CS 141. Hack Society: Projects from the Public Sector. *9 units (0-0-9); second term. Prerequisites: CS/IDS 142, 143, CMS/CS/EE/IDS 144, or permission from instructor.* There is a large gap between

the public and private sectors' effective use of technology. This gap presents an opportunity for the development of innovative solutions to problems faced by society. Students will develop technology-based projects that address this gap. Course material will offer an introduction to the design, development, and analysis of digital technology with examples derived from services typically found in the public sector. Not offered 2019–20.

CS/IDS 142. Distributed Computing. *9 units (3-2-4); first 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. Instructors: Murray, Chandy.

CS/EE/IDS 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 focuses on the link layer (two) through the transport layer (four) of Internet protocols. It has two distinct components, analytical and systems. In the analytical part, after a quick summary of basic mechanisms on the Internet, we will focus on congestion control and explain: (1) How to model congestion control algorithms? (2) Is the model well defined? (3) How to characterize the equilibrium points of the model? (4) How to prove the stability of the equilibrium points? We will study basic results in ordinary differential equations, convex optimization, Lyapunov stability theorems, passivity theorems, gradient descent, contraction mapping, and Nyquist stability theory. We will apply these results to prove equilibrium and stability properties of the congestion control models and explore their practical implications. In the systems part, the students will build a software simulator of Internet routing and congestion control algorithms. The goal is not only to expose students to basic analytical tools that are applicable beyond congestion control, but also to demonstrate in depth the entire process of understanding a physical system, building mathematical models of the system, analyzing the models, exploring the practical implications of the analysis, and using the insights to improve the design. Not offered 2019–20.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. *12 units (3-4-5).* 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/IDS 144 or CS/IDS 142 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. Control and Optimization of Networks. *9 units (3-3-3); first term. Prerequisites: Ma 2, Ma 3 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 in the design, analysis, control, and optimization of networks. Usually offered in odd years. Offered 2019–20. Instructor: Low.

EE/CS 147. Digital Ventures Design. *9 units (3-3-3); first term. Prerequisites: none.* For course description, see Electrical Engineering.

EE/CNS/CS 148. Selected Topics in Computational Vision. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

CS/SS/Ec 149. Algorithmic Economics. *9 units (3-0-6); second term.* This course will equip students to engage with active research at the intersection of social and information sciences, including: algorithmic game theory and mechanism design; auctions; matching markets; and learning in games. Not offered 2019–20.

CS/IDS 150 ab. Probability and Algorithms. *9 units (3-0-6); first term. Prerequisites: part a: CS 38 and Ma 5 abc; part b: part a or another introductory course in discrete probability.* Part a: The probabilistic method and randomized algorithms. Deviation bounds, k-wise independence, graph problems, identity testing, derandomization and parallelization, metric space embeddings, local lemma. Part b: Further topics such as weighted sampling, epsilon-biased sample spaces, advanced deviation inequalities, rapidly mixing Markov chains, analysis of boolean functions, expander graphs, and other gems in the design and analysis of probabilistic algorithms. Parts a & b are offered in alternate years. Part b will be offered in 2019–20. Instructor: Schulman.

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 2019–20.

CS 152. Introduction to Cryptography. *12 units (3-0-9); first term. Prerequisites: Ma 1b, CS 21, CS 38 or equivalent recommended.* This course is an introduction to the foundations of cryptography.

The first part of the course introduces fundamental constructions in private-key cryptography, including one-way functions, pseudo-random generators and authentication, and in public-key cryptography, including trapdoor one-way functions, collision-resistant hash functions and digital signatures. The second part of the course covers selected topics such as interactive protocols and zero knowledge, the learning with errors problem and homomorphic encryption, and quantum cryptography: quantum money, quantum key distribution. The course is mostly theoretical and requires mathematical maturity. There will be a small programming component. Not offered 2019–20.

CS/IDS 153. Current Topics in Theoretical Computer Science. *9 units (3-0-6); third 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/IDS 155. Machine Learning & Data Mining. *12 units (3-3-6).* For course description see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-1-5); 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. Instructor: Abu-Mostafa.

IDS/ACM/CS 157. Statistical Inference. *9 units (3-2-4).* For course description, see Information and Data Sciences.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. *9 units (3-3-3).* For course description, see Information and Data Sciences.

CS/CNS/EE/IDS 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. Not offered 2019–20.

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/CS 161. Big Data Networks. *9 units (3-0-6); third term.* For course description, see Electrical Engineering.

CS/IDS 162. Data, Algorithms and Society. *9 units (3-0-6); third term. Prerequisites: CS 38 and CS 155 or 156a.* This course examines algorithms and data practices in fields such as machine learning, privacy, and communication networks through a social lens. We will draw upon theory and practices from art, media, computer science and technology studies to critically analyze algorithms and their implementations within society. The course includes projects, lectures, readings, and discussions. Students will learn mathematical formalisms, critical thinking and creative problem solving to connect algorithms to their practical implementations within social, cultural, economic, legal and political contexts. Enrollment by application. Taught concurrently with VC 72 and can only be taken once, as VC 72 or CS/IDS 162. Instructor: Mushkin/Ralph.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. *12 units (3-3-6); second term. Prerequisites: CMS/ACM/IDS 113, ACM/EE/IDS 116, CS 156a, ACM/CS/IDS 157 or instructor's permission.* The course assumes students are comfortable with analysis, probability, statistics, and basic programming. This course will cover core concepts in machine learning and statistical inference. The ML concepts covered are spectral methods (matrices and tensors), non-convex optimization, probabilistic models, neural networks, representation theory, and generalization. In statistical inference, the topics covered are detection and estimation, sufficient statistics, Cramer-Rao bounds, Rao-Blackwell theory, variational inference, and multiple testing. In addition to covering the core concepts, the course encourages students to ask critical questions such as: How relevant is theory in the age of deep learning? What are the outstanding open problems? Assignments will include exploring failure modes of popular algorithms, in addition to traditional problem-solving type questions. Instructor: Anandkumar.

EE/CS/IDS 167. Introduction to Data Compression and Storage. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/CNS 171. Computer Graphics Laboratory. *12 units (3-6-3); first term. Prerequisites: Extensive programming experience and proficiency in linear algebra, starting with CS2 and Ma1b.* This is a challenging course that introduces the basic ideas behind computer graphics and some of its fundamental algorithms. Topics include graphics input and output, the graphics pipeline, sampling and im-

age manipulation, three-dimensional transformations and interactive modeling, basics of physically based modeling and animation, simple shading models and their hardware implementation, and some of the 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: Extensive programming experience, CS/CNS 171 or instructor's permission.* This laboratory class offers students an opportunity for independent work including 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 possible improvements to the basic methods. May be repeated for credit with instructor's permission. Instructor: Barr.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. *9 units (3-6-0).* For course description, see Electrical Engineering.

CS 176. Computer Graphics Research. *9 units (3-3-3); second term. Prerequisites: 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. Not offered 2019–20.

CS/ACM 177 ab. Discrete Differential Geometry: Theory and Applications. *9 units (3-3-3); second, third terms.* Working knowledge of multivariate calculus and linear algebra as well as fluency in some implementation language is expected. Subject matter covered: differential geometry of curves and surfaces, classical exterior calculus, discrete exterior calculus, sampling and reconstruction of differential forms, low dimensional algebraic and computational topology, Morse theory, Noether's theorem, Helmholtz-Hodge decomposition, structure preserving time integration, connections and their curvatures on complex line bundles. Applications include elastica and rods, surface parameterization, conformal surface deformations, computation of geodesics, tangent vector field design, connections, discrete thin shells, fluids, electromagnetism, and elasticity. Instructor: Schröder.

CS/IDS 178. Numerical Algorithms and their Implementation. *9 units (3-3-3); second term. Prerequisites: CS 2.* This course gives students the understanding necessary to choose and implement basic numerical algorithms as needed in everyday programming practice. Concepts include: sources of numerical error, stability, convergence, ill-conditioning, and efficiency. Algorithms covered include solution of linear systems (direct and iterative methods), orthogonalization, SVD, interpolation and approximation, numerical integration, solution of ODEs and PDEs, transform methods (Fourier, Wavelet), and low rank approximation such as multipole expansions. Not offered 2019–20.

CS 179. GPU Programming. *9 units (3-3-3); third term. Prerequisites: Good working knowledge of C/C++.* Some experience with computer graphics algorithms preferred. 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 use nVidia's parallel computing architecture, CUDA. Labwork requires extensive programming. Instructor: Barr.

CS 180. Master's Thesis Research. *Units (total of 45) are determined in accordance with work accomplished.*

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. *9 units (3-0-6).* For course description, see Biology.

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 (3-0-6).* For course description, see Bioengineering.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. *12 units ; a (3-6-3) second term; b (2-8-2).* For course description, see Bioengineering.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

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 2019–20.

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.

CS 287. Center for the Mathematics of Information Seminar. *3, 6, or 9 units, at the instructor's discretion; first, second, third terms.* Instructor's permission required. Instructor: Staff.

COMPUTING AND MATHEMATICAL SCIENCES

CMS/ACM/IDS 107. Linear Analysis with Applications. *12 units (3-3-6); first term. Prerequisites: ACM/IDS 104 or equivalent, Ma 1 b or equivalent.* Covers the basic algebraic, geometric, and topological properties of normed linear spaces, inner-product spaces, and linear maps. Emphasis is placed both on rigorous mathematical development and on applications to control theory, data analysis and partial differential equations. Instructor: Stuart.

CMS/ACM/IDS 113. Mathematical Optimization. *12 units (3-0-9); first term. Prerequisites: ACM 11 and ACM 104, or instructor's permission.* 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. Instructor: Chandrasekaran.

CMS 117. Probability Theory and Stochastic Processes. *12 units (3-0-9); first term. Prerequisites: ACM/IDS 104, ACM/EE/IDS 116*

or instructor's permission. This course offers a rigorous introduction to probability and stochastic processes. Emphasis is placed on the interaction between inequalities and limit theorems, as well as contemporary applications in computing and mathematical sciences. Topics include probability measures, random variables and expectation, independence, concentration inequalities, distances between probability measures, modes of convergence, laws of large numbers and central limit theorem, Gaussian and Poisson approximation, conditional expectation and conditional distributions, filtrations, and discrete-time martingales. Instructor: Tropp.

CMS/CS/IDS 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, and ACM/EE/IDS 116 or CMS/ACM/IDS 113 or equivalent.* This course develops core principles for the analysis and design of algorithms. Basic material includes mathematical techniques for analyzing performance in terms of resources, such as time, space, and randomness. The course introduces the major paradigms for algorithm design, including greedy methods, divide-and-conquer, dynamic programming, linear and semidefinite programming, randomized algorithms, and online learning. Instructor: Vidick.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. *12 units (3-4-5); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6 a, and CS 38, or instructor permission.* Social networks, the web, and the internet are essential parts of our lives, and we depend on them every day. This course studies how they work and the "big" ideas behind our networked lives. Questions explored include: 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 expects students to be comfortable with graph theory, probability, and basic programming. Instructor: Wierman.

CMS/CS/CNS/EE/IDS 155. Machine Learning & Data Mining. *12 units (3-3-6); second term. Prerequisites: CS/CNS/EE 156 a.* Having a sufficient background in algorithms, linear algebra, calculus, probability, and statistics, is highly recommended. 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. The course will focus on basic foundational concepts underpinning and motivating modern machine learning and data mining approaches. We will also discuss recent research developments Instructor: Yue.

CMS 270. Advanced Topics in Computing and Mathematical Sciences. *Units by arrangement; second term.* Advanced topics that will vary according to student and instructor interest. May be repeated for credit. Instructor: Murray.

CMS 290 abc. Computing and Mathematical Sciences Colloquium. *1 unit; first, second, third terms. Registration is limited to graduate students in the CMS department only.* This course is a research seminar course covering topics at the intersection of mathematics, computation, and their applications. Students are asked to attend one seminar per week (from any seminar series on campus) on topics related to computing and mathematical sciences. This course is a requirement for first-year PhD students in the CMS department. Instructor: Schröder.

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 or CDS 112 (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: Staff.

CDS 110. Introduction to Feedback Control Systems. *9 units (3-3-3); third 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. Instructor: Seinfeld.

CDS 112. Optimal Control and Estimation. *9 units (3-0-6); second term. Prerequisites: CDS 110 (or equivalent) and CDS 131.* Optimi-

zation-based design of control systems, including optimal control and receding horizon control. Introductory random processes and optimal estimation. Kalman filtering and nonlinear filtering methods for autonomous systems. Instructor: Chung.

CDS 131. Linear Systems Theory. *9 units (3-0-6); first term. Prerequisites: Ma 1b, Ma 2, ACM/IDS 104 or equivalent (may be taken concurrently).* Basic system concepts; state-space and I/O representation. Properties of linear systems, including stability, performance, robustness. Reachability, observability, minimality, state and output-feedback. Instructor: Murray.

CDS 141. Network Control Systems. *9 units (3-2-4); third term.* Variety of case studies and projects from control, communication and computing in complex tech, bio, neuro, eco, and socioeconomic networks, particularly smartgrid, internet, sensorimotor control, cell biology, medical physiology, and human and animal social organization. Emphasis on leveraging universal laws and architectures but adding domain specific details. Can be taken after CDS 231 (to see applications of the theory) or before (to motivate the theory). Not offered 2019–20.

CDS 190. Independent Work in Control and Dynamical Systems. *Units to be arranged; first, second, third terms; maximum two terms. Prerequisite: CDS 110.* Research project in control and dynamical systems, supervised by a CDS faculty member.

CDS 231. Robust Control Theory. *9 units (3-2-4); second term. Prerequisites: CMS/ACM/IDS 107, CMS/ACM/IDS 113, and CDS 131 (or equivalents).* Linear input/output models (multi-state difference and differential equations). Stability, input/output norms. Uncertainty, including noise, disturbances, parametric uncertainty, unmodeled dynamics, and structured uncertainty (LTI/LTV). Tradeoffs, robustness versus efficiency, conservation laws and hard limits in time and frequency domain. Synthesis of robust control systems. Co-design of sparse and limited (delayed, quantized, saturating, noisy) sensing, communications, computing, and actuation. Layering, localization, and distributed control. Interplay between automation, optimization, control, modeling and system identification, and machine learning. Computational scalability exploiting sparsity and structure, nonlinear dynamics and sum of squares, global stability, regions of attraction. Motivation throughout from case studies from tech, neuro, bio, and socioeconomic networks, explored in more detail in CDS 141. Not offered 2019–20.

CDS 232. Nonlinear Dynamics. *9 units (3-0-6); second term. Prerequisites: CMS/ACM/ IDS107 and CDS 231.* This course studies nonlinear dynamical systems beginning from first principles. Topics include: existence and uniqueness properties of solutions to non-

linear ODEs, stability of nonlinear systems from the perspective of Lyapunov, and behavior unique to nonlinear systems; for example: stability of periodic orbits, Poincaré maps and stability/invariance of sets. The dynamics of robotic systems will be used as a motivating example. Instructor: Ames.

CDS 233. Nonlinear Control. *9 units (3-0-6); third term. Prerequisites: CDS 231 and CDS 232.* This course studies nonlinear control systems from Lyapunov perspective. Beginning with feedback linearization and the stabilization of feedback linearizable system, these concepts are related to control Lyapunov functions, and corresponding stabilization results in the context of optimization based controllers. Advanced topics that build upon these core results will be discussed including: stability of periodic orbits, controller synthesis through virtual constraints, safety-critical controllers, and the role of physical constraints and actuator limits. The control of robotic systems will be used as a motivating example. Instructor: Ames.

CDS 242. Hybrid Systems: Dynamics and Control. *9 units (3-2-4); third term. Prerequisites: CDS 231 and CDS 232.* This class studies hybrid dynamical systems: systems that display both discrete and continuous dynamics. This includes topics on dynamic properties unique to hybrid system: stability types, hybrid periodic orbits, Zeno equilibria and behavior. Additionally, the nonlinear control of these systems will be considered in the context of feedback linearization and control Lyapunov functions. Applications to mechanical systems undergoing impacts will be considered, with a special emphasis on bipedal robotic walking. Not offered 2019–20.

CDS 243. Adaptive Control. *4 units (2-0-2); third term. Prerequisites: CDS 231 AND CDS 232.* Specification and design of control systems that operate in the presence of uncertainties and unforeseen events. Robust and optimal linear control methods, including LQR, LQG and LTR control. Design and analysis of model reference adaptive control (MRAC) for nonlinear uncertain dynamical systems with extensions to output feedback. Offered in alternate years. Instructor: Lavretsky.

CDS 244. System Identification. *4 units (2-0-2); third term. Prerequisites: CDS 231 and CDS 232.* Mathematical treatment of system identification methods for dynamical systems, with applications. Nonlinear dynamics and models for parameter identification. Gradient and least-squares estimators and variants. System identification with adaptive predictors and state observers. Parameter estimation in the presence of non-parametric uncertainties. Introduction to adaptive control. Offered in alternate years. Not offered 2019–20.

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: Faculty.

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.

BEM/Ec/PS 80. Frontiers in Social Sciences. *1 unit (1-0-0).* For course description, see Business, Economics and Mangement.

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. Firms, Competition, and 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. Instructor: Shum.

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/ACM/CS 112. Bayesian Statistics. *9 units (3-0-6); second term. Prerequisites: Ma 3, ACM/EE/IDS 116 or equivalent.* This course provides an introduction to Bayesian Statistics and its applications to data analysis in various fields. Topics include: discrete models, regression models, hierarchical models, model comparison, and MCMC methods. The course combines an introduction to basic theory with a hands-on emphasis on learning how to use these methods in practice so that students can apply them in their own work. Previous familiarity with frequentist statistics is useful but not required. Instructor: Rangel.

Ec 117. Matching Markets. *9 units (3-0-6); third term.* We will tackle the fundamental question of how to allocate resources and organize exchange in the absence of prices. Examples includes finding a partner, allocating students to schools, and matching donors to patients in the context of organ transplantations. While the main focus will be on formal models, we will also reason about the practical implications of the theory. Instructor: Pomatto.

BEM/Ec/ESE 119. Environmental Economics. *9 units (3-0-6).* For course description, see Business, Economics, and Management.

Ec 121 ab. Theory of Value. *9 units (3-0-6); first, third terms. Prerequisites: Ec 11 and Ma 1b (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. Instructors: Border, Schenone.

Ec 122. Econometrics. *9 units (3-0-6); first term. Prerequisites: Ma 3.* The application of statistical techniques to the analysis of economic data. Instructor: Sherman.

Ec 123. Econometric Analysis of Discrete Choice. *9 units (3-0-6); second term. Prerequisites: Ec 122.* This course uses advanced econometric tools to analyze why people make the choices that they do in many domains- whether to make investments in peer-to-peer lending, consumer shopping between brands, where to go to college (Caltech or MIT?), choosing between modes of transportation (car, metro, Uber/Lyft, or bicycle), etc. We will focus on applications of discrete choice models (in which the dependent variable to be explained is usually a 0-1, Yes or No choice). The statistical models create estimates of behavioral parameters which describe numerically how much people value different goods or outcomes and how random their responses are. Models studied include logit, nested logit, probit, and mixed logit etc. Simulation techniques that allow estimation of otherwise intractable models will also be discussed. Models of this kind are routinely used in business and government, but are often misused and misinterpreted unless they are deeply understood. Instructor: Xin.

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. Not offered 2019–20.

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 2019–20.

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. Not offered 2019–20.

Ec 131. Market Design. *9 units (3-0-6); first term. Prerequisites: Ec 11, Ec 121, and PS/Ec 172.* The class studies different mechanisms to allocate a scarce resource, frequently called markets, using theoretical models. We will cover centralized markets, which clear via a single price, waiting or rationing, or use centralized algorithms to allocate demand and supply; decentralized markets, which clear via search; and auction markets. In each case, we will study how market rules determine the incentives of market participant and how to design these markets, focusing on efficiency and revenue maximization. Applications to electricity markets, concert tickets, ride-sharing, labor markets, school choice, dating markets, sponsored search ad auctions, and spectrum auctions will be covered. Instructor: Doval.

Ec 135. Economics of Uncertainty and Information. *9 units (3-0-6); first term. Prerequisite: Ec 11.* 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 136. Behavioral Decision Theory. *9 units (3-0-6); second term. Prerequisites: Ma 3. Ec 121 is recommended as background, but is not a prerequisite.* This course is an intermediate-level class on individual-level theory. The method used posits precise assumptions about general behavior (axioms) then finds equivalent ways to model them in mathematically convenient terms. We will cover both the traditional "rational" approach, and more recent "behavioral" models that incorporate psychological principles, in domains of intertemporal choice, random (stochastic) choice, menu choice, and revealed preferences. Students are expected to understand rigorous mathematical proofs. The class also includes serious discussion of the value of experimental evidence motivating new theories. Instructors: Saito.

Ec 140. Economic Progress. *9 units (3-0-6); third term. Prerequisites: Ec 11; 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. Instructors: Hoffman.

CS/SS/Ec 149. Algorithmic Economics. *9 units (3-0-6).* For course description, see Computer Science.

BEM/Ec 150. Business Analytics. *9 units (3-0-6). 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 ab. Convex Analysis and Economic Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 1. Ec 121a is recommended.* Introduction to the use of convex analysis in economic theory. Includes separating hyperplane theorems, continuity and differentiability properties of convex and concave functions, support functions, subdifferentials, Fenchel conjugates, saddlepoint theorem, theorems of the alternative, polyhedra, linear programming, and duality in graphs. Introduction to discrete convex analysis and matroids. Emphasis is on the finite-dimensional case, but infinite-dimensional spaces will be discussed. Applications to core convergence, cost and production functions, mathematical finance, decision theory, incentive design, and game theory. Instructor: Border.

ELECTRICAL ENGINEERING

EE 1. The Science of Data, Signals, and Information. *9 units (3-0-6); third term.* Electrical Engineering has given rise to many key developments at the interface between the physical world and the information world. Fundamental ideas in data acquisition, sampling, signal representation, and quantification of information have their origin in electrical engineering.This course introduces these ideas and discusses signal representations, the interplay between time and frequency domains, difference equations and filtering, noise and denoising, data transmission over channels with limited capacity, signal quantization, feedback and neural networks, and how humans interpret data and information. Applications in various areas

of science and engineering are covered. Satisfies the menu requirement of the Caltech core curriculum. Instructor: Vaidyanathan.

EE 2. Electrical Engineering Entrepreneurial and Research Seminar. *1 unit; second term. Required for EE undergraduates.* Weekly seminar given by successful entrepreneurs and EE faculty, broadly describing their path to success and introducing different areas of research in 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, specifically, research going on at Caltech and in the industry. Instructor: Emami.

EE/ME 7. Introduction to Mechatronics. *6 units (2-3-1); first 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/CS 10 ab. Introduction to Digital Logic and Embedded Systems. *6 units (2-3-1); second, third terms.* 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. The course will cover basic digital logic, programmable logic devices, CPU and embedded system architecture, and embedded systems programming principles (interfacing to hardware, events, user interfaces, and multi-tasking). Instructor: George.

EE 13. Electronic System Prototyping. *3 units (0-3-0); first term.* This course is intended to introduce the student to the technologies and techniques used to fabricate electronic systems. The course will cover the skills needed to use standard CAD tools for circuit prototyping. This includes schematic capture and printed circuit board design. Additionally, soldering techniques will be covered for circuit fabrication as well as some basic debugging skills. Each student will construct a system from schematic to PCB to soldering the final prototype. Instructor: George.

APh/EE 23. Demonstration Lectures in Classical and Quantum Photonics. *9 units (3-0-6).* For course description, see Applied Physics.

APh/EE 24. Introductory Optics and Photonics Laboratory. *9 units (1-3-5).* For course description, see Applied Physics.

EE 40. Physics of Electrical Engineering. *9 units (3-0-6); third term.* This course provides an introduction to the fundamental physics of modern device technologies in electrical engineering used for sensing, communications, computing, imaging, and displays. The course overviews topics including semiconductor physics, quantum mechanics, electromagnetics, and optics with emphasis on physical operation principles of devices. Example technologies include integrated circuits, optical and wireless communications, micromechanical systems, lasers, high-resolution displays, LED lighting, and imaging. Instructor: Marandi.

EE 44. Deterministic Analysis of Systems and Circuits. *12 units (4-0-8); first term. Prerequisites: Ph 1 abc, can be taken concurrently with Ma 2 and Ph 2 a.* Modeling of physical systems by conversion to mathematical abstractions with an emphasis on electrical systems. Introduction to deterministic methods of system analysis, including matrix representations, time-domain analysis using impulse and step responses, signal superposition and convolution, Heaviside operator solutions to systems of linear differential equations, transfer functions, Laplace and Fourier transforms. The course emphasizes examples from the electrical circuits (e.g., energy and data converters, wired and wireless communication channels, instrumentation, and sensing) , while providing some exposure to other selected applications of the deterministic analysis tool (e.g., public opinion, acoustic cancellation, financial markets, traffic, drug delivery, mechanical systems, news cycles, and heat exchange). Instructor: Hajimiri.

EE 45. Electronics Systems and 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 53. Microprocessor Project Laboratory. *12 units (0-12-0); first, second, third terms. Prerequisites: EE/CS 10 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. Not offered 2019–20. Instructor: George.

CS/EE/ME 75 abc. 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 and third terms;* 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: Staff.

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: Ohanian.

EE 91 ab. Experimental Projects in Electronic Circuits. *9 units (1-8-0); first, second terms. Prerequisites: EE 45. Recommended: EE/CS 10 ab, and EE/MedE 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. Instructor: Ohanian.

576

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: Emami.

ACM/EE 106 ab. Introductory Methods of Computational Mathematics. *12 units (3-0-9);* For course description, see Applied and Computational Mathematics.

ME/EE/EST 109. Energy Technology and Policy. *9 units (3-0-6); first term.* For course description, see Mechanical Engineering.

EE 110 abc. Embedded Systems Design Laboratory. *9 units (3-4-2); first, second, third terms.* The student will design, build, and program a specified microprocessor-based embedded system. This structured laboratory is organized to familiarize the student with large-scale digital and embedded system design, electronic circuit construction techniques, modern development facilities, and embedded systems programming. The lectures cover topics in embedded system design such as display technologies, interfacing to analog signals, communication protocols, PCB design, and programming in high-level and assembly languages. Given in alternate years; Offered 2019–20. Instructor: George.

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. Instructor: Vaidyanathan.

EE 112. Introduction to Signal Processing from Data. *9 units (3-0-6); second term. Prerequisites: EE 111 or equivalent. Math 3 recommended.* Fundamentals of digital signal processing, extracting information from data by linear filtering, recursive and non-recursive filters, structural and flow graph representations for filters, data-adaptive filtering, multirate sampling, efficient data representations with filter banks, Nyquist and sub-Nyquist sampling, sensor array signal processing, estimating direction of arrival (DOA) information from noisy data, and spectrum estimation. 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. Instructor: 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. Not offered 2019–20. Instructor: Hajimiri.

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 2019–20.

ACM/EE/IDS 116. Introduction to Probability Models. *9 units (3-1-5).* For course description, see Applied and Computational Mathematics.

Ph/APh/EE/BE 118 abc. Physics of Measurement. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

EE/CS 119 abc. Advanced Digital Systems Design. *9 units (3-3-3); first, second term; 9 units (1-8-0) third term. Prerequisites: EE/CS 10 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 tech-

nologies and tools. Given in alternate years; not offered 2019–20. Instructor: George.

EE 121. Computational Signal Processing. *(3-0-9); first. Prerequisites: EE 111, ACM/EE/IDS 116, ACM/IDS 104.* The role of computation in the acquisition, representation, and processing of signals. The course develops methodology based on linear algebra and optimization, with an emphasis on the interplay between structure, algorithms, and accuracy in the design and analysis of the methods. Specific topics covered include deterministic and stochastic signal models, statistical signal processing, inverse problems, and regularization. Problems arising in contemporary applications in the sciences and engineering are discussed, although the focus is on the common abstractions and methodological frameworks that are employed in the solution of these problems. Not offered 2019–20. Instructor: Chandrasekaran.

EE/MedE 124. Mixed-mode Integrated Circuits. *9 units (3-0-6); third term. Prerequisites: EE 45 a or equivalent. I*ntroduction 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. Instructor: Emami

EE/CS/MedE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0); third 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, combinational-arithmetic, 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. Instructor: Pedroni.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisites: Ma 3.* 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, Markov, ergodic, and Gaussian. Calculation of capacity and rate-distortion functions. Universal source codes. Side infor-

mation 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/IDS 127, EE/CS 161, and EE/CS/IDS 167, should prepare the student for research in information theory, coding theory, wireless communications, and/or data compression. Instructor: Effros.

EE/Ma/CS/IDS 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. The students will become acquainted with encoding and decoding algorithms, design principles and performance evaluation of codes. Instructor: Kostina.

EE 128 ab. Selected Topics in Digital Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: EE 111 and EE/CS/IDS 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 2019–20.

ME/CS/EE 129. Experimental Robotics. *9 units (3-6-0).* For course description, see Mechanical Engineering.

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. Not offered 2019–20. Instructor: Yariv.

APh/EE 132. Special Topics in Photonics and Optoelectronics. *9 units (3-0-6); third term.* For course description, see Applied Physics.

ME/CS/EE 133 abc. Robotics. *9 units (3-3-3).* For course description, see Mechanical Engineering.

ME/CS/EE 134. Robotic Systems. *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. Prerequisites: EE 44, Ma 2, or equivalent.* Basic power system analysis: phasor representation, 3-phase transmission system, transmission line models, transformer models, per-unit analysis, network matrix, power flow equations, power flow algorithms, optimal powerflow (OPF) problems, swing dynamics and stability. Current research topics such as (may vary each year): convex relaxation of OPF, frequency regulation, energy functions and contraction regions, volt/var control, storage optimization, electric vehicles charging, demand response. Instructor: Low.

EE/Ma/CS/IDS 136. Topics in Information Theory. *9 units (3-0-6); third term. Prerequisites: undergraduate calculus and probability.* 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. Not Offered 2019–20. Instructor: Kostina.

CS/EE/IDS 143. Communication Networks. *9 units (3-3-3).* For course description, see Computer Science.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. *12 units (3-4-5).* 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. Control and Optimization of Networks. *9 units (3-3-3).* For course description, see Computer Science.

EE/CS 147. Digital Ventures Design. *9 units (3-3-3); first term. Prerequisites: none.* This course aims to offer the scientific foundations of analysis, design, development, and launching of innovative

digital products and study elements of their success and failure. The course provides students with an opportunity to experience combined team-based design, engineering, and entrepreneurship. The lectures present a disciplined step-by-step approach to develop new ventures based on technological innovation in this space, and with invited speakers, cover topics such as market analysis, user/product interaction and design, core competency and competitive position, customer acquisition, business model design, unit economics and viability, and product planning. Throughout the term students will work within an interdisciplinary team of their peers to conceive an innovative digital product concept and produce a business plan and a working prototype. The course project culminates in a public presentation and a final report. Every year the course and projects focus on a particular emerging technology theme. Not offered 2019–20. Instructor: Staff.

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. Instructor: Perona.

EE/APh 149. Frontiers of Nonlinear Photonics. *9 units (3-0-6); second term.* This course overviews recent advances in photonics with emphasis on devices and systems that utilize nonlinearities. A wide range of nonlinearities in the classical and quantum regimes is covered, including but not limited to second- and third-order nonlinear susceptibilities, Kerr, Raman, optomechanical, thermal, and multi-photon nonlinearities. A wide range of photonic platforms is also considered ranging from bulk to ultrafast and integrated photonics. The course includes an overview of the concepts as well as review and discussion of recent literature and advances in the field. Instructor: Marandi.

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 152. High Frequency Systems Laboratory. *12 units (2-3-7); first term. Prerequisites: EE 45 or equivalent. EE 153 recommended.* The student will develop a strong, working knowledge of high-frequency systems covering RF and microwave frequencies. The essential building blocks of these systems will be studied along with the fundamental system concepts employed in their use. The first part of the course will focus on the design and measurement of core system building blocks; such as filters, amplifiers, mixers, and oscillators. Lectures will introduce key concepts followed by weekly laboratory sessions where the student will design and characterize these various system components. During the second part of the course, the student will develop their own high-frequency system, focused on a topic within remote sensing, communications, radar, or one within their own field of research. Instructor: Russell.

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.

EE 154 ab. Practical Electronics for Space Applications. *9 units (2-3-4); second and third terms.* Part a: Subsystem Design: Students will be exposed to design for subsystem electronics in the space environment, including an understanding of the space environment, common approaches for low cost spacecraft, atmospheric / analogue testing, and discussions of risk. Emphasis on a practical exposure to early subsystem design for a TRL 3-4 effort. Part b: Subsystems to System Interfacing: Builds upon the first term by extending subsystems to be compatible with "spacecraft", including a near-space "flight" of prototype subsystems on a high-altitude balloon flight. Focus on qualification for the flight environment appropriate to a TRL 4-5 effort. Not Offered 2019–20. Instructor: Klesh.

CMS/CS/CNS/EE/IDS 155. Machine Learning & Data Mining. *12 units (3-3-6).* For course description, see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-1-5).* 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-infra-red 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/IDS 159. Advanced Topics in Machine Learning. *9 units (3-0-6).* For course description, see Computer Science.

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. *9 units (3-0-6); second term.* Basics of information theory: entropy, mutual information, source and channel coding theorems. Basics of coding theory: error-correcting codes for information transmission and storage, block codes, algebraic codes, sparse graph codes. Basics of digital communications: sampling, quantization, digital modulation, matched filters, equalization. Instructor: Kostina.

EE/CS 161. Big Data Networks. *9 units (3-0-6); third term. Prerequisites: Linear Algebra ACM/IDS 104 and Probability and Random Processes ACM/EE/IDS 116 or their equivalents.* Next generation networks will have tens of billions of nodes forming cyber-physical systems and the Internet of Things. A number of fundamental scientific and technological challenges must be overcome to deliver on this vision. This course will focus on (1) How to boost efficiency and reliability in large networks; the role of network coding, distributed storage, and distributed caching; (2) How to manage wireless access on a massive scale; modern random access and topology formation techniques; and (3) New vistas in big data networks, including distributed computing over networks and crowdsourcing. A selected subset of these problems, their mathematical underpinnings, state-of-the-art solutions, and challenges ahead will be covered. Given in alternate years. Not offered 2019–20. Instructor: Hassibi.

EE 163. Communication Theory. *9 units (3-0-6); second term. Prerequisites: EE 111; ACM/EE/IDS 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. Capacity measures; multiple antenna and multiple carrier communication systems; wireless networks; different generations of wireless systems. Not Offered 2019–20. Instructor: Staff.

EE 164. Stochastic and Adaptive Signal Processing. *9 units (3-0-6); third term. Prerequisite: ACM/EE/IDS 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 2019–20. Instructor: Hassibi.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. *12 units (3-3-6).* For course description, see Computer Science.

EE/CS/IDS 167. Introduction to Data Compression and Storage. *9 units (3-0-6); third term. Prerequisites: Ma 3 or ACM/EE/IDS 116.* The course will introduce the students to the basic principles and techniques of codes for data compression and storage. The students will master the basic algorithms used for lossless and lossy compression of digital and analog data and the major ideas behind coding for flash memories. Topics include the Huffman code, the arithmetic code, Lempel-Ziv dictionary techniques, scalar and vector quantizers, transform coding; codes for constrained storage systems. Given in alternate years; Not offered 2019–20. Instructor: Kostina.

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. *9 units (4-0-5).* For course description, see Medical Engineering.

ACM/EE/IDS 170. Mathematics of Signal Processing. *12 units (3-0-9).* For course description, see Applied and Computational Mathematics.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. *9 units (3-6-0); third term. Prerequisites: medium to advanced knowledge of digital electronics.* A careful balance between synthesis and analysis in the development of digital circuits plus a truly complete coverage of the VHDL language. The RTL (register transfer level) approach. Study of FPGA devices and comparison to ASIC alternatives. Tutorials of software and hardware tools employed in the course. VHDL infrastructure, including lexical elements, data types, operators, attributes, and

complex data structures. Detailed review of combinational circuits followed by full VHDL coverage for combinational circuits plus recommended design practices. Detailed review of sequential circuits followed by full VHDL coverage for sequential circuits plus recommended design practices. Detailed review of state machines followed by full VHDL coverage and recommended design practices. Construction of VHDL libraries. Hierarchical design and practice on the hard task of project splitting. Automated simulation using VHDL testbenches. Designs are implemented in state-of-the-art FPGA boards. Instructor: Pedroni.

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.

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 2019–20.

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 2019–20.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. *189 a, 12 units (3-6-3) offered both first and third terms. 189b, 9 units (0-9-0) offered only third term.* For course description, see Bioengineering.

ACM/EE/IDS 217. Advanced Topics in Stochastic Analysis. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

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

ME/EE/EST 109. Energy Technology and Policy. *9 units (3-0-6).* For course description, see Mechanical Engineering.

EE/CS/EST 135. Power System Analysis. *9 units (3-3-3).* For course description, see Electrical Engineering.

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: Umans.

E/VC 88. Critical Making. *9 units (3-0-6); third term.* This course examines the concepts and practices of maker culture through hands-on engagement, guest workshops, lectures, reading and discussions on the relations between technology, culture and society. Classes may include digital fabrication, physical computing, and other DIY technologies as well as traditional making. Major writings and practitioners' work may be covered from the study of maker culture, DIY culture, media, critical theory, histories of science, design and art. Not offered 2019–20. Instructor: Mushkin.

E/H/VC 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. Instructor: Mushkin.

E 100. Special Topics in Engineering Applied Science. *Units to be arranged; terms to be arranged; offered by announcement. Prerequisites: none.* Content may vary from year to year, at a level suitable for advanced undergraduate or graduate students. Topics will be chosen to meet the emerging needs of students. Instructors: TBD.

E/SEC 102. Scientific and Technology Entrepreneurship. *9 units (3-0-6); third term.* This course introduces students to the conceptual frameworks, the analytical approaches, the personal understanding and skills, and the actions required to launch a successful technology-based company. Specifically, it addresses the challenges of evaluating new technologies and original business ideas for commercialization, determining how best to implement those ideas in a startup venture, attracting the resources needed for a new venture (e.g., key people, corporate partners, and funding), organizing and operating a new enterprise, structuring and negotiating important business relationships, and leading early stage companies toward "launch velocity". Instructor: TBD.

E/SEC 103. Management of Technology. *9 units (3-0-6); first term.* A course intended for students interested in learning how rapidly evolving technologies are harnessed to produce useful products or fertile new area for research. Students will work through Harvard Business School case studies, supplemented by lectures to elucidate the key issues. There will be a term project where students predict the future evolution of an exciting technology. The course is team-based and designed for students considering choosing an exciting research area, 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 assess-

ment, technology trend methodologies (scenarios, projections), motivation, rewards and recognition. Industries considered will include electronics (hardware and software), aerospace, medical, biotech, etc. Students will perform both primary and secondary research and through analysis present defensible projections. E/SEC 102 and E/ME/MedE 105 are useful but not required precursors. Instructor: TBD.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); terms to be arranged; offered by announcement.* 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. Instructor: TBD.

E 110. Principles of University Teaching and Learning in STEM. *3 units (2-0-1); first term, second term.* This graduate course examines the research on university-level STEM (science, technology, engineering, and mathematics) teaching and learning, which has been used to inform a well-established body of evidence-based teaching practices. 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 explore the roles of active learning, student engagement, and inclusive teaching practices in designing classes where all students have an equal opportunity to be successful and feel a sense of belonging, both in the course and as scientists. Readings will inform in-class work and students will apply principles to a project of their choice. Instructors: Horii, Weaver.

ENGLISH

Hum/En 20. Greek Epic and Drama. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 21. The Marvelous and the Monstrous: Literature at the Boundaries of the Real. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 22. Inequality. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 23. Literature and Medicine. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 24. The Scientific Imagination in English Literature. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 25. The Human Animal. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 29. Dream Narratives. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 33. Modern Metamorphoses. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 35. Major British Authors. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 36. American Literature and Culture. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 37. Modern European Literature. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 38. Telling Time in American Modernism. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 39. Contemporary American Fiction. *9 units (3-0-6).* For course description, see Humanities.

En 83. History of the English Language. *9 units (3-0-6); third 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 2019–20.

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.

En 85. Poetry Writing. *9 units (3-0-6); third term.* When William Blake wrote "to see a World in a Grain of Sand," he tapped into poetry's power to model the universe. For instance, once we set up a simile between "world" and "grain of sand", we can test this hypothesis of sameness. How is sand like the world? Where will the model fail? And what might that tell us? Imagery, sensory language, arguments, ideas, and verse form itself can lead poetry toward power and discovery. This pursuit can reach from the page into one's own life. We will work hard together on poems, our own and one another's. Students may apply one term of 85, 86, or 89 to the additional HSS requirements, and all other courses in this series will receive institute credit. Instructors: Factor.

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, or 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. Students may apply one term of En 85, 86, or 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. 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, dranma, lyrics, romances, selections from Chaucer's Canterbury Tales, and Malory's Morte Darthur. Readings will be in Middle and modern English. Not offered 2019–20.

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. Not offered 2019–20.

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. Not offered 2019–20.

En 106. Poetic Justice: Histories of Literature and Law. *9 units (3-0-6); third term.* How does literature help us to frame questions of equity and fairness? How do writers represent broad concepts like the "common good" or the "body politic," and what does poetry do in the world to shape political action and ideas? This course takes the long historical view on these questions, exploring the overlapping histories of law and literary representation within premodern and contemporary contexts. We will ask how literature thinks about problems of justice, violence, and mercy, and how the courtroom becomes a key site for representing the dramas of social inclusion and exclusion. Possible authors and texts include Dante, Chaucer, Langland, Shakespeare, and Behn. Instructor: Jahner. Not offered 2019–20.

En 107. Medieval Romance. *9 units (3-0-6); second 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. Instructor: Jahner. Not offered 2019–20.

En/VC 108. Volcanoes. *9 units (3-0-6); first term.* Long before torrents of lava cascaded down Los Angeles streets in the 1997 film Volcano, volcanic disaster narratives erupted across 19th-century British pages, stages, and screens. This class will examine the enduring fascination with volcanoes in literary and visual culture and the socio-political tensions that disaster narratives expose. Students will analyze Mary Shelley's Frankenstein and Tambora's infamous 1815 eruption, James Pain's 1880s pyrotechnic adaptation of Vesuvius's 79AD eruption, and paintings of global sunsets after Krakatoa's 1883 eruption. Additional literary and visual texts may include works by: Felicia Hemans, Isabella Bird, M.P. Shiel, Charles Dickens, Sir Edward Bulwer-Lytton, and J. M. W. Turner. Instructor: Sullivan.

En 109. Madness and Reason. *9 units (3-0-6); second term.* Madness threatens to dissolve boundaries of the most various kinds:

between the human and the inhumane, reality and fantasy, sickness and health. One of the tasks of a literary text is to subdue and contain madness through the construction of rational frameworks. How does a literary text accomplish this? Which strategies, such as the use of irony and humor, are the most effective? What role do insane characters play in literary texts? And when - if ever - should we consider an excess of reason as a kind of madness in its own right? Selected readings from Shakespeare, Voltaire, Goethe, Hoffmann, Büchner, Gogol, and Schnitzler, among others. Instructor: Holland.

En 110. Sinners, Saints, and Sexuality in Premodern Literature. *9 units (3-0-6); third term.* What made the difference between saint and sinner in medieval and Renaissance literature? This class takes up this question by focusing on the unruly problems of embodiment. We will read across a wide range of literatures, including early medical texts, saints' lives, poetry and romance, as we examine how earlier periods understood gender and sexual difference. Questions we may consider include the following: how did writers construct the "naturalness" or "unnaturalness" of particular bodies and bodily acts? How did individuals assert control over their own bodies and those of others? In what ways did writing authorize, scrutinize, or police the boundaries of the licit and illicit? Finally, how have modern critics framed these questions? Possible readings include Aristotle, Freud, Chaucer, Margery Kempe, Christine de Pizan, Sidney, Shakespeare. Instructor: Jahner. Not offered 2019–20.

En 113. Shakespeare's Career: Comedies and Histories. *9 units (3-0-6).* The first of a two-course sequence on Shakespeare's career as a dramatist and poet. We will read plays from the first half of Shakespeare's career, his comedies and histories. Particular attention will be paid to Shakespeare's use of his sources and to the textual history of the plays. En 113 and En 114 may be taken independently and, usually, are taught in alternate years. Instructor: Pigman. Not offered 2019–20.

En 114. Shakespeare's Career: Tragedies and Tragicomedies. *9 units (3-0-6); third term.* The second of a two-course sequence on Shakespeare's career as a dramatist and poet. We will read works from the second half of Shakespeare's career, his tragedies, tragicomedies, and Sonnets. Particular attention will be paid to Shakespeare's use of his sources and to the textual history of the plays. En 113 and En 114 may be taken independently and, usually, are taught in alternate years. Instructor: Pigman.

En/VC 117. Picturing the Universe. *9 units (3-0-6); second term.* Whether you are a physicist, photographer, or bibliophile, grab a warm jacket. The night sky beckons. In addition to observing and photographing our own starry skies, we will study 19th-century

literary, artistic, and scientific responses to new understandings of the universe as dynamic, decentered, and limitless. In Victorian England, picturing the universe in literature and recording celestial light in photographs defied the physiological limitations of human observation and fueled larger debates about objective evidence and subjective documentation. Authors studied may include: Anna Laetitia Aikin, Keats, Byron, Tennyson, Hardy, Agnes Clerke, E. E. Barnard, Tracy Smith, and Dava Sobel. Instructor: Sullivan.

En 118. Classical Mythology. *9 units (3-0-6); first 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. Not offered 2019–20.

En 119. Displacement. *9 units (3-0-6); first 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 2019–20.

En 120. What Women Want: Desire and the Modern American Novel. *9 units (3-0-6); second term.* The question of what a woman wants animates a central strain of the modern American novel, as do evolving ideas about what women can and cannot have. This course considers female desire-for personal agency and freedom, self- and sexual fulfillment, economic and social opportunity-across a half dozen novels written from about 1880 - 1940, in light of some of the cultural forces that shape and constrain characters' (and real women's) horizons. Authors covered may include Henry James, Edith Wharton, Theodore Dreiser, Anzia Yezierska, Nella Larsen, and Zora Neale Hurston. Instructor: Jurca.

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 Sopho-

cles' 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. Not offered 2019–20.

En 122. Early History of the Novel. *9 units (3-0-6); third 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 2019–20.

En 123. The 19th-Century English Novel. *9 units (3-0-6); first 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 2019–20.

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 2019–20.

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. Not offered 2019–20.

En 126. Gothic Fiction. *9 units (3-0-6); second 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 2019–20.

En 127. Jane Austen. *9 units (3-0-6); second 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. Instructor: Gilmartin.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); first 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. Not offered 2019–20.

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 2019–20.

En 134. The Career of Herman Melville. *9 units (3-0-6); third term.* The course will analyze Melville's career starting with Typee and ending with Billy Budd. Special attention will be given to Moby-Dick and Pierre. The centrality of Melville's position in American literature will be considered from a variety of perspectives, including aesthetics, representations of race, class, and gender, the role of the audience, and connections with other authors. Instructor: Weinstein.

En 135. Dickens's London. *9 units (3-0-6); third term.* Charles Dickens and London have perhaps the most famous relationship of any writer and city in English. In this course, we will investigate

both the London Dickens knew, and the portrait of the city that he painted, by reading some of Dickens's great mid-career novels alongside a selection of primary and secondary historical sources. We will think about the gap-or overlap- between history and fiction, the idea of the novelist as alternative historian, and the idea of the novel as historical document. Historical topics covered may include: the development of the Victorian police force; plague and public health; Victorian poverty; colonialism and imperialism; Dickens and his illustrators; Victorian exhibition culture; and marriage and the cult of domesticity, among others. In addition to written work, students should expect to be responsible for making a short research presentation at some point in the term. Instructor: Gilmore. Not offered 2019–20.

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 2019–20.

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 2019–20.

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 2019–20.

En 139. Reading Resistance in Cold War American Literature. *9 units (3-0-6); first term.* This course will examine the complexities and contradictions of US Cold War culture. Through literary texts featuring a diverse range of protagonists, we will engage characters who question the status quo, often by exploring the limits and exclusions of national belonging in this period. Though the 1950s saw the rise of McCarthyism and the threat of nuclear war, landmark events in these years also galvanized the civil rights

movement and demands for social justice. Course readings in Cold War fiction, drama, and poetry will demonstrate how mainstream social identities conditioned by racial, class, gender and sexual norms, were being challenged and subverted in ways that would intensify and take on collective expression in the 1960s. Authors studied may include: Gwendolyn Brooks, William Demby, Lorraine Hansberry, Jack Kerouac, William S. Burroughs, Carson McCullers, Mitsuye Yamada, Sylvia Plath, and John Okada. Instructor: Sherazi. Not offered 2019–20.

En 140. African American Expatriate Culture in Postwar Europe. *9 units (3-0-6); first term.* In the years following World War II, an unprecedented number of African American writers, artists, and intellectuals moved to Paris and Rome, many seeking greater personal liberties and a refuge from racial discrimination at home. As we explore literature, nonfiction, and visual culture created by African Americans in postwar Europe, we will consider how and why the postwar creative scene in Paris differed from that of Rome. We will analyze postwar African American expatriate writing's critical perspectives and insights regarding American society and culture, particularly regarding desegregation and postwar social identities. Our discussions will identify the literary strategies that writers used to address the changing times, promote social justice, and advance new narrative forms, often by crossing traditional boundaries of genre and nation. Authors studied may include: James Baldwin, Richard Wright, Barbara Chase-Riboud, William Demby, Maya Angelou, and Ralph Ellison. Instructor: Sherazi. Not offered 2019–20.

En 141. Contemporary African American Literature. *9 units (3-0-6); first term.* This course will engage works of contemporary African American literature, including Ishmael Reed's experimental novel Mumbo Jumbo (1972) and Octavia Butler's time-travel novel Kindred (1979) and selected Afrofuturist short stories. We will read critical essays about temporality and consider these authors' use of temporal strategies, including anachronisms, non-linear narration, historiography, and the creation of speculative worlds. How does the artistic project of narrating the racialized past create possibilities for imagining alternative futures? The course will analyze the role of slavery, trauma, and collective memory in our readings, and it will set these literary texts in conversation with Afrofuturist music and visual culture from the 1970s to the present. Students will have the opportunity to examine archival materials from the Huntington Library related to Octavia Butler's published fiction. Instructor: Sherazi. Not offered 2019–20.

En 142. Post-1945 American Literature and 'The Death of the Author'. *9 units (3-0-6); first term.* This course will explore the ambiguous status of literature that is published in the wake of an author's death. Should "unfinished" work be edited and published

in the late author's name? What if the author left behind no express wishes for her/his unpublished writing or asked that it be destroyed? Alongside such questions, we will analyze posthumously published post-1945 American literature's formal features and its engagements with socio-political transformations related to race, class, gender, and sexuality. Course readings will include Roland Barthes' "The Death of the Author" (1967) and Michel Foucault's "What is an Author?" (1969), as well as posthumously published modernist fiction and poetry by authors including Ralph Ellison, Sylvia Plath, Jack Kerouac and William Burroughs Instructors: Sherazi.

En 150. Chaos and Literature. *9 units (3-0-6); second term.* We tend to think of literary texts as models of a stable poetic order, but modern and postmodern writers conduct increasingly bold experiments to test the contrary. This class explores how writers from the nineteenth century onward draw upon ancient and contemporary concepts of chaos to test out increasingly sophisticated models of disorder though writing. Readings to include Lucretius, Serres, Calvino, Barth, Stoppard, and Kehlmann. Instructor: Holland. Not offered 2019–20.

En/VC 160 ab. Classical Hollywood Cinema. *9 units (3-0-6); second term.* This course introduces students to Hollywood films and filmmaking during the classical period, from the coming of sound through the '50s. Students will develop the techniques and vocabulary appropriate to the distinct formal properties of film. 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. Part b not offered 2019–20. Instructor: Jurca.

En/VC 161. The New Hollywood. *9 units (3-0-6); first 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 especially in the representation of violence and sexuality. 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. Not offered 2019–20.

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 2019–20.

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 2019–20.

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 criti-

cally to give a sense of the totality of this greatest British regional novelist's achievement. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

En 186. The Novel of Education. *9 units (3-0-6); third term.* This class takes up a set of mostly very funny, mostly 20th century British novels to frame a simple-seeming, yet deceptively complicated set of questions: What does it mean to be educated? Who has

access to education? What does an ideal education consist in? And ultimately: What is a university for? As we think through these questions we will read op/eds and investigative journalism in addition to fiction, and we will consider a variety of university-centered topics (determined by student interest) including issues of gender, class, privilege, race, and genius. Authors read may include Sayers, Larkin, Amis, C.P. Snow, Lodge, 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. Not offered 2019–20.

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 2019–20.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. *9 units (3-0-6); first 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 nine-teenth 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. Not offered 2019–20.

ENGLISH AS A SECOND LANGUAGE

Please see page 324 for requirements regarding English compe-tency. All of the following courses are open to international graduate students only.

ESL 101 ab. Oral Communication and Presentation. *3 units (3-0-0); first, second terms.* This course focuses on preparing non-native speakers of English with the communication skills necessary to organize, present or exchange information in a clear, concise man-ner to a variety of audiences. ESL 101a will provide instruction on the development of pronunciation, intonation patterns and stress, grammar and verb tense, listening comprehension, and fluency in speaking. Aspects of American culture as well as come current events will be discussed. ESL 101b is a continuation of ESL 101a, and covers a variety of oral presentation skills. Students will be asked to paraphrase, summarize, and synthesize information from a journal article or in-class discussions and communicate ideas to the class. The class will discuss information from readings and other media sources in small groups to collect and organize ideas for dis-cussion. ESL 101ab is open to all first-year graduate students and may be required for some students designated by the ESL interview process during Orientation. A passing grade will satisfy the Institute English proficiency requirement for candidacy. Graded pass/fail. In-structor: Staff.

ESL/Wr 107. Graduate Writing Seminar. *6 units (3-0-3); third term.* This course provides guided instruction in academic writing in STEM fields. More specifically, it teaches graduate students about composing texts in scientific English for expert audiences. It helps familiarize writers with academic STEM discourse, and it teaches writers about the style and genres of U.S. academic STEM writing, helping them learn to locate, read, and write about the work of oth-ers in their field. From here, students learn to review the literature in their fields and situate their own research goals within that context. Students are encouraged to take ESL/Wr 107 in the first or second year of graduate school. This course is designed for non-native

speakers of English, but it covers topics that are relevant to native English speakers. Instructor: Staff.

ESL/Wr 108. Intermediate Graduate Writing Seminar. *6 units (3-0-3); summer term.* This course focuses on strategies for composing an academic journal article in a STEM field. The rhetorical purpose and form of each section of the journal article will be considered in depth. The course is intended for graduate students who are prepared to be a lead author on a manuscript. While the course will cover strategies for collaborative writing, students will be asked to draft sections of an original journal article based upon their own research. The course will also provide instruction on selecting a target journal, preparing a manuscript for submission, and responding to feedback from peer reviewers. Clarity in scientific writing and creating effective figures will also be discussed. This course is designed for non-native speakers of English, but it covers topics that are relevant to native English speakers. Course enrollment is limited to 15 students. Instructor: Staff.

ENVIRONMENTAL SCIENCE AND ENGINEERING

ESE 1. Earth's Climate. *9 units (3-0-6); third term.* An introduction to the coupling between atmospheric composition and climate on Earth. How Earth's climate has changed in the past and its evolving response to the rapid increase in carbon dioxide and methane happening today. Model projections of future climate and associated risks. Development of climate policies in face of uncertainty in these projections and risks. Enrollment is limited. Satisfies the menu requirement of the Caltech core curriculum. Juniors and Seniors who have satisfied their menu course requirement should enroll in ESE 101. Instructor: Wennberg.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. *6 units (2-0-4).* For course description, see Freshman Seminars.

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.* Introduction to the fundamental processes governing atmospheric circulations and climate. Starting from an overview of the observed state of the atmosphere and its variation over the past, the course discusses Earth's radiative energy balance including the greenhouse effect, Earth's orbit around the Sun and climatic effects of its variations, and the role of atmospheric circulations in maintaining the energy, angular momentum, and water balances, which determine the distributions of temperatures, winds, and precipitation. The focus throughout is on order-of-magnitude physics that is applicable to climates generally, including those of Earth's past and future and of other planets. Instructor: Schneider.

ESE 102. Earth's Oceans. *9 units (3-0-6); first term.* This course will provide a basic introduction to physical, chemical and biological properties of Earth's ocean. Topics to be covered include: oceanographic observational and numerical methods as well as the phenomenology and distribution of temperature, salinity, and tracers. Fundamentals of ocean dynamics, such as Ekman layers, wind-driven gyres, and overturning circulations. Ocean biology and chemistry: simple plankton population models, Redfield ratios, air-sea gas exchange, productivity and respiration, carbon cycle basics. Changes in ocean circulation over Earth's history and its impact on past climate changes. Instructor: Thompson.

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: Frankenberg.

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: Thompson.

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: Frankenberg.

Ge/ESE 118. Methods in Data Analysis. *9 units (3-0-6); first term. Prerequisites: Ma 1 or equivalent.* For course description, see Geology.

BEM/Ec/ESE 119. Environmental Economics. *9 units (3-0-6).* For course description, see Business, Economics, and Management.

ESE 130. Introduction to Atmosphere and Ocean Dynamics. *9 units (3-0-6); second term. Prerequisites: ESE 101/102 or instructor's permission.* Introduction to geophysical fluid 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: Callies.

ESE 131. Ocean Dynamics. *9 units (3-0-6); third term. Prerequisites: ESE 130 or instructor's permission.* This course gives an in-depth discussion of the fluid dynamics of the world ocean. Building on the concepts developed in ESE 130, this course explores the vertical structure of the wind-driven gyre circulation, thermocline theory, eddies and eddy parameterizations, the circulation of the deep ocean, ocean energetics, surface gravity waves, tides, internal waves, and turbulent mixing. Instructors: Callies, 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. Instructor: Staff. Not offered 2019–20.

ESE 133. Global Atmospheric Circulations. *9 units (3-0-6); second term. Prerequisites: ESE 130 or instructor's permission.* Introduction to the global-scale fluid dynamics of atmospheres, beginning with a phenomenological overview of observed circulations on Earth and other planets and leading to currently unsolved problems. Topics include constraints on atmospheric circulations and zonal winds from angular momentum balance; Rossby wave generation,

propagation, and dissipation and their roles in the maintenance of global circulations; Hadley circulations and tropical-extratropical interactions; energy cycle and thermodynamic efficiency of atmospheric circulations. The course focuses on Earth's atmosphere but explores a continuum of possible planetary circulations and relationships among them as parameters such as the planetary rotation rate chance. Instructor: Staff. Not offered 2019–20.

ESE 134. Cloud and Boundary Layer Dynamics. *9 units (3-0-6); third term. Prerequisites: ESE 130 or instructor's permission.* Introduction to the dynamics controlling boundary layers and clouds and how they may change with climate, from a phenomenological overview of cloud and boundary layer morphologies to closure theories for turbulence and convection. Topics include similarity theories for boundary layers; mixed-layer models; moist thermodynamics and stability; stratocumulus and trade-cumulus boundary layers; shallow cumulus convection and deep convection. Instructor: Schneider. Offered 2019–20.

ESE 135. Topics in Atmosphere and Ocean Dynamics. *6 units (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. Instructor: Callies. Not offered 2019–20.

ESE 136. Climate Models. *6 units (2-0-4); third term. Prerequisites: ESE 101 or instructor's permission.* Introduction to climate models, from numerical methods for the underlying equations of motion to parameterization schemes for processes such as clouds, sea ice, and land hydrology. The course will move from an overview of modeling concepts to the practice of climate modeling, with hands-on exercises in running a climate model and analyzing and understanding its output. It will enable students to design their own model experiments and to evaluate modeling results critically. Instructor: Schneider. Not offered 2019–20.

ESE 137. Polar Oceanography. *9 units (3-0-6); third term. Prerequisites: ESE 131 or instructor's permission.* This course focuses on high latitude processes related to the the Earth's oceans and their interaction with the cryosphere, including glaciers, ice shelves and sea ice. The course starts with introductory lectures related to regional circulation features, water mass modification and ice dynamics. A single topic will be selected to explore in detail through the scientific literature and through individual projects. Instructor: Thompson. Given in alternate years; Offered 2019–20.

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 feedback 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. Instructor: Staff. Not offered 2019–20.

Ge/ESE 139. Introduction to Atmospheric Radiation. *9 units (3-0-6).* For course description in Geological and Planetary Sciences.

Ge/ESE 140 c. Stable Isotope Biogeochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ESE/Ge 142. Aquatic Chemistry of Natural Waters. *9 units (3-0-6); third term. Prerequisites: Ch 1 or instructor's permission.* Inorganic chemistry of natural waters with an emphasis on equilibrium solutions to problems in rivers, lakes, and the ocean. Topics will include, acid-base chemistry, precipitation, complexation, redox reactions, and surface chemistry. Examples will largely be drawn from geochemistry and geobiology. Selected topics in kinetics will be covered based on interest and time. Instructor: Adkins.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

ESE 144. Climate from Space. *9 units (3-0-6); second term.* Introduction to satellite remote sensing. Earth's energy balance. Atmospherics physics and composition. Ocean dynamics and ice physics from space. The water, energy and carbon cycles. The Earth's biosphere from space. The climate system. Instructors: Teixeira, Thompson.

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.

ESE 156. Remote Sensing of the Atmosphere and Biosphere.
9 units (3-0-6); first term. An introduction into methods to quantify trace gases as well as vegetation properties remotely (from space, air-borne or ground-based). This course will provide the basic concepts of remote sensing, using hands-on examples to be solved in class and as problem-sets. Topics covered include: Absorption spectroscopy, measurement and modeling techniques, optimal estimation theory and error characterization, applications in global studies of biogeochemical cycles and air pollution/quality. This course is complementary to EE/Ae 157ab and Ge/EE/ESE 157c with stronger emphasis on applications for the atmosphere and biosphere. Students will work with real and synthetic remote sensing data (basic knowledge of Python advantageous, will make use of Jupyter notebooks extensively). Instructor: Frankenberg.

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); second 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. Instructors: Seinfeld, Flagan. Not offered 2019–20.

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. Instructor: Newman. Given in alternate years; not offered 2019–20.

Ge/ESE/Bi 178. Microbial Ecology. *9 units (3-2-4).* 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. Offered 2019–20.

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. Instructors: Seinfeld, Wennberg. Not offered 2019–20.

ESE/Ch 175. Physical Chemistry of Engineered 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 engineered water systems and related water treatment processes. Lectures cover basic principles of physical-organic and physical-inorganic chemistry relevant to the aquatic environment under realistic conditions. Specific topics include acid-base chemistry, metal-ligand chemistry, redox reactions, photochemical transformations, biochemical transformations, heterogeneous surface reactions, catalysis, and gas-transfer dynamics. The primary emphasis during the winter term course will be on the physical chemistry of engineered waters. Instructor: 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. Instructor: 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
(For course descriptions, please see Visual Culture page 735)

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. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

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: Beyond Physics. *6 units (2-0-4); second, third terms of freshman year and first term of sophomore year.* Freshmen are offered the opportunity to enroll in this class by submitting potential solutions to problems posed in the fall term. A small number of solutions will be selected as winners, granting those students permission to register. This course demonstrates how research ideas arise, are evaluated, and tested and how the ideas that survive are developed. Weekly group discussions and one-on-one meetings with faculty allow students to delve into cutting edge scientific research. Ideas from physics are used to think about a huge swath of problems ranging from how to detect life on extrasolar planets to exploring the scientific underpinnings of science fiction in Hollywood films to considering the efficiency of molecular machines. Support for summer research at Caltech between freshman and sophomore years will be automatic for students making satisfactory progress. Graded pass/fail. Freshmen only; limited enrollment. Instructor: Phillips.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. *6 units (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. Instructor: Ramakrishnan.

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. Not offered 2019–20.

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. Not offered 2019–20.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. *6 units (2-0-4); first term.* To paraphrase a Caltech engineering colleague: "In terms of Earth and the Environment, although fascinating, until recently our species had been nothing more than the hood ornament on a really interesting car. We should be studying what's under the hood, the microbial world, if we want to understand the engine". We will examine striking examples of microbes and microbial activities in the environment. There is one required field trip to visit sites of microbial interest somewhere in southern California. Freshmen only; limited enrollment. Instructor: Leadbetter.

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. 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: Thompson.

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. The causes and recent history of climate change. The course includes an overnight 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: Wernicke.

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 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 Seminars.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. *6 units (2-0-4).* For course description, see Freshman Seminars.

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 overnight field trip, selected laboratory exercises, and problem sets. Instructor: Wernicke.

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.* 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. *Units to be arranged.* Practice in the effective organization and the delivery of oral presentation of scientific results before groups. Units and scheduling are done by the individual options. Graded pass/fail. Instructor: Staff.

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 2019–20.

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); third 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 sedimen-

tary 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 2019–20.

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 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, the use of the petrographic microscope, and optical methods of mineral identification. 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. Instructor: Stolper. Given in alternate years; offered 2019–20.

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. Instructor: Eiler. Given in alternate years; not offered 2019–20.

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. Bayesian Statistics and Data Analysis. *9 units (3-0-6); second term. Prerequisites: CS1 or equivalent.* 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. Instructor: Knutson.

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: Staff. Not offered 2019–20.

Ge 120 a. Field Geology: Introduction to Field Geology. *9 units (1-6-2); third term. Prerequisites: Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106).* A comprehensive introduction to methods of geological field mapping 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: Bucholz.

Ge 120 b. Field Geology: Summer Field Camp. *15 units (0-15-0); summer. Prerequisites: Ge 120 a or instructor's permission.* Intensive three-week field course in a well-exposed area of the western United States covering techniques of geologic field observation, mapping, analysis, and report preparation. Field work begins in mid-June after Commencement Day. Instructor: Bucholz.

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), Stock (b), Grotzinger (c).

Ge 122 abc. Field Geology Seminar. *6 units (1-3-2); first, second, third terms. 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. Topic: tbd. Graded pass/fail. Instructor: Stock. Not offered 2019–20.

Ge 123. Continental Crust Seminar. *3 units (1-0-2); third term.* A seminar course focusing on a topic related to the continental crust, which will be decided depending on the interest of participating students. Potential topics include arc magmatism, the evolution of the composition of continental crust through time, formation of granites, or specific localities/regions that help shape our understanding of continental crust generation. The course will comprise weekly student-lead discussion of scientific journal articles. Instructor: Bucholz.

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. Instructor: Kirschvink. Given in alternate years; not offered 2019–20.

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. Instructor: Kirschvink. Given in alternate years; not offered 2019–20.

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. Instructor: Lamb. Not offered 2019–20.

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. Offered 2019–20.

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. Instructor: Burnett. Given in alternate years; offered 2019–20.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); first 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. Instructor: Blake. Given in alternate years; offered 2019–20.

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. Instructor: Blake. Given in alternate years; not offered 2019–20.

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, gi-
ant impacts, extrasolar planetary systems. Instructor: Batygin.

**Ge 136 abc. Regional Field Geology of the Southwestern United
States.** *3 units (1-0-2); first, second, or third terms, by announce-
ment. 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 ma-
jor 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 as-
sociated with tidal and planet-disk interactions will be considered.
Instructor: Batygin.

Ge/ESE 139. Introduction to Atmospheric Radiation. *9 units
(3-0-6); second term. Prerequisites: Ma 2, Ph 2, or instructor's per-
mission.* The basic physics of absorption and scattering of light by
molecules, aerosols, and clouds. Theory of radiative transfer. Band
models, correlated-k distributions and other approximate methods.
Solar insolation, thermal emission, heating rates and radiances. Ap-
plications to Earth, Planets and Exoplanets. 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, chemi-
cal 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. Instructor: Eiler. Taught in odd years; alternates
with Ge 140b. Not offered 2019–20.

Ge 140 b. Radiogenic Isotope Geochemistry. *9 units (3-0-6); sec-
ond term.* An introduction to the principles and applications of

radiogenic isotope systems in earth science, with emphasis on the applications of these systems, from dating to forensic. Topics to be covered include nucleosynthesis, radioactive decay phenomena, geochronology, geochronometry, isotopes as tracers of solar system and planetary evolution, extinct radioactivities, cosmogenic isotopes and forensic geochemistry. Instructor: Tissot. Taught in even years; alternates with Ge 140a. Offered 2019–20.

Ge/ESE 140 c. Stable Isotope Biogeochemistry. *9 units (3-0-6); third term. Prerequisites: Ge 140a or equivalent.* An introduction to the use of stable isotopes in biogeochemistry, 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. Offered 2019–20.

Ge 141. Isotope Cosmochemistry. *9 units (3-0-6); first term.* An introduction to the study of the origin, abundances and distribution of the elements and their isotopes in the Universe, with emphasis on isotopic constraints into the conditions, events and processes that shaped our Solar System. Topics to be covered include: cosmology and the age of the Universe, the age of the Milky Way and the duration of nucleosynthesis, the fundamentals of isotopic fractionations, the key roles of isotopic anomalies in understanding Solar System dynamics, early Solar System chronology from short- and long-lived nuclei, chondritic meteorite components as clues to solar nebula and asteroid evolution, as well as planetary formation and chronology (e.g., Moon, Mars, Earth). Instructor: Tissot. Not offered 2019–20.

ESE/Ge 142. Aquatic Chemistry of Natural Waters. *9 units (3-0-6); third term.* For course description, see Environmental Science and Engineering.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4); third 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 CO_2 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. Instructor: Sessions. Not offered 2019–20.

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 reassembly 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. Taught in odd-numbered years; offered 2019–20.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6); second 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. Instructor: Adkins. Given in alternate years; offered 2019–20.

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); second 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; not offered 2019–20.

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.* Analysis of electromagnetic radiation at visible, infrared, and radio wavelengths for interpretation of the 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 does not require but is complementary to EE 157ab with 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. Not offered 2019–20.

Ge/Ay 159. Astrobiology. *9 units (3-0-6); second term.* We approach the age-old questions "Why are we here?" and "Are we alone?" by covering topics in cosmology, the origins of life, planetary habitability, the detection of biosignatures, the search for extraterrestrial intelligence, and humanity's future in space. Specific topics include: the emergence of life at hydrothermal vents; the habitable zone and the Gaia hypothesis; the search for ancient habitable environments on Mars; icy satellites like Europa, Enceladus, and Titan as astrobiological prospects; and the hunt for atmospheric biosignatures on exoplanets. Instructor: Yung. Given in alternate years; not offered 2019–20.

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); second 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: Zhan.

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); first 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 and Seismic Imaging. *9 units (3-0-6); first term. Prerequisites: basic linear algebra and Fourier transforms.* Introduction to modern digital analysis: discrete Fourier transforms, filters, correlation, convolution, deconvolution and autoregressive models. Imaging with seismic reflection and refraction data, tomography, receiver functions and surface waves. Instructor: Clayton. Offered 2019–20.

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. Instructor: Staff. Given in alternate years; not offered 2019–20.

Ge 167. Tectonic Geodesy. *9 units (3-0-6); second 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 2019–20.

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.

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. Offered in alternate years; offered 2019–20.

Ge/ESE/Bi 178. 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 2019–20. Instructor: Orphan.

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 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 this 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 geobiological sciences. Students may enroll for any or all terms of this 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; second term. 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/or 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. Instructor: Staff.

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 2019–20.

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. Instructor: Rossman. Given in alternate years; not offered 2019–20.

Ge 215. Topics in Advanced Petrology. *9 units (3-0-6); 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. Instructor: Asimow. Given in alternate years; not offered 2019–20.

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 2019–20.

Ge 219. Non-traditional Isotopes Seminar. *6 units (2-0-4); third term. Prerequisites: Ge 140a or b, or permission of instructor.* The course deals with advanced topics in stable and radiogenic isotope geo-/cosmochemistry and builds on Ge 140a and b, with emphasis on non-traditional isotope systems (Mg, Fe, Ti, Mo, U, etc.). Starting with close examination of seminal papers, each topic will build up to a discussion of the remaining outstanding questions. Topics to be covered will be guided by class interests. Example subjects could include: the early solar system, extinct radioactivities, nucleosynthetic anomalies, the early Earth, paleoredox reconstructions, medical use of stable isotopes. All participants will lead discussions of papers and present a lecture on a relevant subject. Grades will include participation, a review/proposal paper, and oral examination(s). Instructor: Tissot.

631

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/Ge 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

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); second term.* 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: Zhan.

Ge 263. Computational Geophysics. *9 units (3-0-6); first 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. Instructors: Clayton, Gurnis. Given in alternate years; not offered 2019–20.

Ge 264. Machine Learning in Geophysics. *9 units (3-0-6); third term. Prerequisites: Ge 118 or equivalent.* An overview of machine learning algorithms and their usage in current geophysical research. Both supervised and unsupervised learning will be covered. Algorithms include deep neural networks, ensemble learning, clustering, and dimensionality reduction. The course will address data requirements, current limitations, and the role of machine learning in the future of geophysics. Instructor: Ross.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6).* For course description, see Aerospace.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Mechanical Engineering.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

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; not offered 2019–20.

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. Given in alternate years; offered 2019–20.

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. American History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 2. Which Side Are You On? 20th Century African American History Through Debate. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3. The United States in the Twentieth Century. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 5. The History of the Chinese Empire. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 8 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 8 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 8 c. Civilization, Science, and Archaeology: The Nature of Religious Beliefs in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 9 a. European Civilization: The Classical and Medieval Worlds. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 9 b. European Civilization: Early Modern Europe. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 9 c. European Civilization: Modern Europe. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 10. Medieval Europe: The Problem of Violence. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 11. Love and Death: Using Demography to Study the History of Europe from 1700. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 18. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

H 60. Reading in History. *Units to be determined for the individual by the division; 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.

E/H/VC 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. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

H 111. The Medieval Church. *9 units (3-0-6); first 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. Instructor: Brown. Not offered 2019–20.

H 112. The Vikings. *9 units (3-0-6); second 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? Instructor: Brown.

H 115 abc. British History. *9 units (3-0-6); second term.* 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. Part a and c not offered in 2019–20. Instructor: Styles.

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 2019–20.

H 123. Ordinary People: Uncovering Everyday Life in the European Past. *9 units (3-0-6); second term.* In the historical record, much attention is given to wealthy elites (rulers and lawmakers, aristocrats, wealthy merchants), since they were the ones who left written records of their political and economic activities and their personal affairs. But what about the vast majority of people who lived in the past, most of whom were barely literate and had little opportunity to 'make history'? What can we know about them? This class focuses on the lives of ordinary people, and the sources historians use to learn about them. Special attention will be given to women, the poor, and other marginalized groups in societies ranging from England in the west to Russia in the east. Instructor: Dennison.

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 2019–20.

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. Not offered 2019–20.

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 postmodern theorists, which provide intellectual underpinning for experimenting with new forms of history. Not offered 2019–20.

H 131. History of Extinction. *9 units (3-0-6); first term.* Humans are in the midst of the sixth mass extinction—the first to be caused by human activity. Extinction has been viewed in changing ways over the past 200 years, and this course takes an interdisciplinary approach to learning about the extinction process from a historical as well as a modern perspective. Our focus will be on the extinction of biological entities, but we will also touch on other systems that have disappeared: languages, technologies, habitats, and ways of living. Central to our endeavors will be asking what it means to live in this time of loss: Should we mourn? And if so, how do we mourn for what many or most of us do not see, but only read about? Finally, we will scrutinize what the practical effects of extinction have been, are, and will be. We will also make at least one visit to a natural history museum to view some extinct species behind the scenes. Instructor: Lewis. Not offered 2019–20.

H 132. Humanistic Ecology. *9 units (3-0-6); third term.* Humans' conceptions of nature have changed dramatically over time. Ecological systems influence human culture, politics, law, and many other spheres, and in turn, humans influence those systems. This class introduces students to the field of humanistic ecology—a

discipline that looks to a number of cultural, political, historical and economic elements to better understand the role of ecology in a larger sphere outside of its scientific structure and uses. Humanistic ecology is designed to provide context for the study of ecology, and in a fundamental way, focuses on the appropriate role of humanity in its relationship to nature: what is ethical, or not, what is useful, or not, and a variety of other matters that should be considered when taking a fully three-dimensional view of ecological science. Instructor: Lewis. Not offered 2019–20.

H 133. Forests and Humans. *9 units (3-0-6); first term.* Forests - which cover 31 percent of the world's land surface - have played essential roles in enhancing the planet's biodiversity. Forests have also served humans in numerous and often controversial ways, and have also been subjected to dramatic change through human activity. How well have we served forests, as well as being served by them? The class will cover the growth and use of forests from a humanistic and historic perspective, as well as discussions about the role of fire in forests, with a particular emphasis on the unprecedented forest fires in California in the past several years and the global ecological implications. Instructor: Lewis.

H 134. Birds, Evolution, Speciation and Society. *9 units (3-0-6); third term.* The cultural, scientific, social and political roles of birds make them an excellent lens through which to view humans' interactions with the natural world. This course will cover our changing understandings of birds, starting with hawking and falconry in earlier centuries, through the discovery of new species, up through Darwinian understandings of speciation and evolution, and continuing up to present scientific understandings of birds' capabilities and their ties to humankind, as well as to other anchors in the natural world. We will take a strong biographical as well as avian approach to understanding key personalities who furthered our understandings of avian science. Instructor: Lewis.

H 135. War, Conquest, and Empires. *9 units (3-0-6); first 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 136. Caltech in the Archives. *9 units (3-0-6); first term.* This class will introduce students to the methods of archival work in the humanities and social sciences. Over the course of the quarter students will receive an introduction to factors surrounding the collection, organization, and use of various types of archives as a

background to several small-scale projects working in an archival collection of their own choosing. The seminar will center around weekly projects and synthetic analytical essays about the archival process and archival discoveries. Students hoping to combine their course work with an archive-based research paper may sign up for a separate independent study and conduct research concurrently, with instructor approval. Instructor: Dykstra.

H 137. Criminals, Outlaws, and Justice in a Thousand Years of Chinese History. *9 units (3-0-6); second term.* This course explores the shifting boundary between discourses of crime and disobedience over the last millennium or so of Chinese history. It offers fictional, philosophical, political, propagandistic, official, and personal writings on crime and those who commit it as a basis for a wide-ranging series of discussions about when breaking the law is good, when breaking the law is bad, and who gets to decide where the line between a criminal and an outlaw should be drawn. Instructor: Dykstra. Not offered 2019–20.

H 138. The Way. *9 units (3-0-6); second term.* This course introduces students to some of the seminal writings on the meaning of life, the essentials of rulership, and the place of the individual in the universe from the history of Chinese thought and philosophy. Students are given selected readings from several schools of thought in Chinese history, with an emphasis on the formative Warring States era (the period of the Hundred Schools of classical Chinese philosophy). Instead of being asked to write expository or argumentative essays, participants in this seminar will be introduced to analyzing and presenting texts using the method of annotation. Exposure to the principles of annotation will provide students with a new approach to analyzing and talking about texts both within a humanistic context and beyond. Not offered 2019–20. Instructor: Dykstra.

H 139. Translation Theory and Practice (Chinese Historical Sources Seminar). *9 units (3-0-6).* For course description, see L 139. Instructor: Dykstra.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6); first 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. Instructor: Dennison.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

H 149. Age of Fracture: America Since 1974. *9 units (3-0-6); second term.* In this course, we will examine America after Richard Nixon's resignation in 1974, a period that historians have referred to as an age of fracture and social disaggregation. Using fracture as a conceptual framework to investigate American politics and culture in the last quarter of the twentieth century, we'll consider how the recent past has informed present-day American society. Themes of study will include the culture wars, political polarization, globalization, and the growing wealth gap. In addition, we'll investigate the theoretical and methodological challenges of doing recent history. Instructor: Wiggins.

H 150. America in the 1960s. *9 units (3-0-6); first term.* The course adopts a thematic approach to the "long 1960s," engaging in depth with the political, social, and cultural trends that shaped the decade. Topics include the African American struggle for civil rights, the "urban crisis," Cold War culture, liberalism at high tide, the Vietnam War, sexual liberation, the New Left and counterculture, as well as the rise of the New Right. Throughout, the course interrogates the privileged role given the 1960s in American history, questioning to what extent the decade marked a departure from the American past or a continuation of long-running trends. Instructor: Savage.

H 151. The Long(er) Civil Rights Movement: From Emancipation to Black Lives Matter. *9 units (3-0-6); third term.* Taking historian Jacqueline Dowd Hall's call to expand the chronology of the civil rights narrative rather generously, this course explores African American freedom struggles over a period bookended by emancipation and the Black Lives Matter movement. Through an analysis of a wide array of historical sources, the course will also examine topics such as Reconstruction, the rise of Jim Crow, the Great Migration, the civil rights movement of the 1950s and 1960s, Northern and Western segregation, and mass incarceration. Instructor: Savage.

H 152. Where Do We Go from Here? Black America in the Post-Civil Rights Era. *9 units (3-0-6); first term.* This course will examine African American politics, culture, and society in the decades following the passage of landmark civil rights legislation in the 1960s. Topics of discussion will include deindustrialization and the rise of hip hop culture, black feminist and queer thought, debates over welfare and affirmative action, and mass incarceration. Analyzing a variety of political and cultural artifacts as well as cutting-edge

secondary literature, we will investigate various moments in recent African American history to gain insight into changing notions of rights, citizenship, equality, and freedom in American society. Instructor: Wiggins.

HPS/H 160. 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); first term.* Instructor: Styles.

HPS/H 162. Social Studies of Science. *9 units (3-0-6).* 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 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 180. Forbidden Knowledge. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

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 multi-national 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 2019–20.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. *9 units (3-0-6); second 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. Not offered 2019–20.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. *9 units (3-0-6); second term.* This course covers a broad range of topics in the history of maps and exploration from Antiquity to the present. These topics range from the earliest visualizations of earth and space in the Classical world to contemporary techniques in interplanetary navigation. By way of maps, students will explore various ways in which different cultures have conceptualized and navigated earth and space. While maps emulate the world as perceived by the human eye, they, in fact, comprise a set of observations and perceptions of the relationship between bodies in space and time. Thus, students will study maps, and the exploration they enable, as windows to the cultures that have produced them, not only as scientific and technical artifacts to measure and navigate our world. Instructors: Wey-Gomez, Ceva.

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 fed-

erated 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 2019–20.

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 2019–20.

H 189. The Ethics of War. *9 units (3-0-6); third term.* We tend to think of violence as a breakdown in social order, but warfare, as an organized form of violence, complicates this perspective. Can waging war and upholding justice go hand in hand? In this seminar, we will explore theories of just war from Classical antiquity through the Middle Ages, paying particular attention to methods of categorizing warfare, women at war, and pacifist critiques. The course will conclude by assessing depictions of medieval warfare in contemporary culture, such as Vikings or Game of Thrones. Readings may include Aristotle, Cicero, Augustine, Thomas Aquinas, medieval handbooks of chivalry, Ælfric of Eynsham, documents from the trial of Joan of Arc, and Thomas More. Not offered 2019–20.

H/L 191. Perspectives on History through German Literature. *9 units (3-0-6); third 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. Not offered 2019–20.

H 192. The Crusades. *9 units (3-0-6); third 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? Instructor: Brown.

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 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 2019–20.

En/H 197. American Literature and the Technologies of Reading. *9 units (3-0-6); For course description, see English.*

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 18. Introduction to the History of Science. *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/PI/CS 110. Causation and Explanation. *9 units (3-0-6); third 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/PI 120. Introduction to Philosophy of Science. *9 units (3-0-6); first 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: Sebens.

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 2019–20.

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. Instructor: Sebens.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6); second 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. Instructor: Hubert.

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? Instructor: Hubert.

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. Instructor: Hitchcock. Not offered 2019–20.

HPS/Pl 136. Happiness and the Good Life. *9 units (3-0-6); first 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. Instructor: 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 160. 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/Pl 165. Selected Topics in Philosophy of Science. *9 units (3-0-6).* 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).* third term. *Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently).* 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); third term. Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently).* 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. Instructor: Buchwald. Not offered 2019–20.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6).* Instructors: Staff, visiting lecturers.

HPS/H 170. History of Light from Antiquity to the 20th Century.
9 units (3-0-6); second, third terms. Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently). 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. Instructor: Buchwald, J. Not offered 2019–20.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6). Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently).* 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 2019–20.

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 2019–20.

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 2019–20.

HPS/H 180. Forbidden Knowledge. *9 units (3-0-6); first term.* Why does the notion of freedom of knowledge and teaching in science and engineering matter? What kinds of restrictions have been placed on scientists and engineers, their publications and institutions? Who restrained scientific and engineering knowledge of what sorts; for what reasons; and how successfully? These questions will be addressed by exploring the strategies developed by the U.S. research community to protect the international circulation of knowledge after World War II, when scientific freedom and the export of technical data had to be balanced with the needs of national security. Case studies will include the atomic bomb, the semiconductor industry in the 1970s and space technologies, notably rockets/missiles, in the 1990s. The threat to U.S. economics and military security posed by the Soviet Union in the Cold War, and by China today, has transformed the practice of research in university and in industry alike building new walls around the production and circula-

tion of knowledge to affirm national sovereignty that is, all the while, being undermined by the global circulation of trained scientists and engineers. Instructor: Krige.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. *9 units (3-0-6).* For course description, see History.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. *9 units (3-0-6).* For course description, see History.

HUMANITIES

Hum/H 1. American History. *9 units (3-0-6); first term.* 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 2. Which Side Are You On? 20th Century African American History Through Debate. *9 units (3-0-6); second term.* In this introductory course, we will discuss twentieth-century African American history by examining debates that have defined black politics, culture, and society. With a focus on analyzing primary sources and critiquing secondary literature, we will trace the contours of historical and historiographical debates in African American history and gain an understanding of the diversity of thought and experience among black Americans. Instructor: Wiggins.

Hum/H 3. The United States in the Twentieth Century. *9 units (3-0-6); first term.* Designed to introduce students to the academic study of history, this course examines key issues and events that shaped the political, social, and cultural history of the United States in the Twentieth Century. Through a wide variety of historical sources—including primary documents, fiction, and music—students will explore issues such as popular culture, immigration and labor, the civil rights movement, political realignment, and American intervention abroad. Instructor: Savage.

Hum/H 5. The History of the Chinese Empire. *9 units (3-0-6); first term.* This class will explore several facets of how the concept of empire and its historical formation in China was defined, portrayed, and developed over time. It offers students a chance to reflect on the interaction of event, record, and remembrance as these components combine in the creation and contestation of history. This course will particularly emphasize how the making, writing, and remembering of history responds to the advent of different regimes of legitimacy in order to give students a new perspective on the relationship between action, authorship, and interpretation in history. Instructor: Dykstra.

Hum/H 8 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. *9 units (3-0-6); third term.* 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. Instructor: Buchwald. Not offered 2019–20.

Hum/H 8 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. *9 units (3-0-6); second, third terms.* 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. Instructors: Buchwald, J.

Hum/H 8 c. Civilization, Science, and Archaeology: The Nature of Religious Belief in Ancient Egypt, Mesopotamia, and Israel. *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 2019–20.

Hum/H 9 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. Not offered 2019–20.

Hum/H 9 b. European Civilization: Early Modern Europe. *9 units (3-0-6); first, second, third terms.* 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: Hoffman, Wey-Gomez.

Hum/H 9 c. European Civilization: Modern Europe. *9 units (3-0-6); third term.* 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.

Hum/H 10. Medieval Europe: The Problem of Violence. *9 units (3-0-6); second, third terms.* This course will explore how people understood violence in Europe between ca. 500 and ca. 1400 AD. It will focus on the various norms that governed the use of violence in a period when the right of free people to carry and use weapons was considered self-evident. Working through primary sources, students will explore the relationship between violence and vengeance, the law, central authority and public order, religion, emotions, public ritual, and economics. As they go along students will consider whether violence can coexist with or even promote stable, ordered societies, or whether it by definition creates disorder. Instructor: Brown.

Hum/H 11. Love and Death: Using Demography to Study the History of Europe from 1700. *9 units (3-0-6); first, second terms.* Demographic events—births, marriages, deaths—have always been

highly responsive to changes in the local environment. Decisions about when to marry, how many children to have, or what kind of household to live in have always been closely correlated to decisions people take in other areas of their lives and, as a result, can tell us a great deal about the economic, social, and cultural worlds people inhabit. This course examines differences in demographic trends in Europe across space and time, from 1700 to the present, as well as existing explanations for these differences, including political economic factors, social and cultural norms, biology and disease environments. Some topics include: the demographic effects of war, industrialization, and urbanization; changes related to the emergence of reliable contraceptive technologies; changes related to the expansion of economic opportunities for women; the effects of government policies on demographic decisions. Instructor: Dennison.

Hum 15. Special Topics in Humanities. *9 units (3-0-6); offered by announcement.* This course will count as a freshman humanities course in either English, history, philosophy, or visual culture, as announced. It is usually taught by new or visiting faculty. The course may be re-taken once if the second class is offered in a different discipline (from among English, history, philosophy, and visual culture). Limited to 15 students. See registrar's announcement for details. Instructor: Staff.

Hum/H/HPS 18. Introduction to the History of Science. *9 units (3-0-6); second, third terms.* 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/En 20. Greek Epic and Drama. *9 units (3-0-6); first, second terms.* The epic poems attributed to Homer, the Iliad and the Odyssey, and Athenian drama of the fifth and early fourth centuries BCE have been masterpieces of the western literary tradition for thousands of years. We will study one or both epics, tragedies by Aeschylus, Sophocles, and Euripides, and comedies by Aristophanes. Instructor: Pigman.

Hum/En 21. The Marvelous and the Monstrous: Literature at the Boundaries of the Real. *9 units (3-0-6); second, third terms.* Marvels flourish at the boundaries of literary invention, religious belief, and scientific inquiry, challenging assumptions about natural processes and expected outcomes. From Grendel, the monstrous foe of Beowulf, to Satan, Milton's charismatic antihero, this seminar examines the uses of the marvelous in a variety of texts and genres, including Shakespearian drama, medieval romance, and early travel-writing. Readings may include Beowulf, Marie de France, Chaucer, John Mandeville, Shakespeare, Milton. Instructor: Jahner. Not offered 2019–20.

Hum/En 22. Inequality. *9 units (3-0-6); second term.* Throughout the history of Europe, America, and beyond, poets and philosophers have asked hard questions about unequal relationships, whether between kings and subjects, gods and humans, men and women, rich and poor, or machines and people. Our authors take no single point of view; our goal is to analyze sophisticated and often surprising arguments and to enter new cultural worlds. Readings may include Ovid, Milton, Sei Shonagon, Machiavelli, Rousseau, and Alexievich. Instructor: Haugen.

Hum/En 23. Literature and Medicine. *9 units (3-0-6); third term.* The relationship between patients and doctors, the ill and the well, involves a constant exchange of stories. In this course we will look more closely at the relationship between medicine and narrative through a selection of fiction, essays and poems that investigate the interplay between doubt and diagnosis, the idea of the case study, the problem of medical responsibility, and the language of pain and illness. Authors covered may include Sontag, Mantel, Conan Doyle, Freud, Woolf, Dickinson, Ishiguro and Shelley. Instructor: Gilmore. Not offered 2019–20.

Hum/En 24. The Scientific Imagination in English Literature. *9 units (3-0-6); third term.* This course considers three periods of major scientific development—the Renaissance, the nineteenth century, and the modern period— to explore the influence new ideas, discoveries, and theories had on the imagination of English writers. We will look at the early modern interplay between magic and science, Romantic and Victorian debates about evolution, and the twentieth-century advent of modern physics as we confront consistent tropes like the mad scientist, the scientist-hero, and the problem of uncertainty. Authors covered may include Shakespeare, Marlowe, Bacon, Shelley, Darwin, Conan Doyle, Stevenson, Auden, McEwan, and Stoppard. Instructor: Gilmore.

Hum/En 25. The Human Animal. *9 units (3-0-6); second term.* European literature has long been a testing ground for radical new ideas which have come to shape our basic understanding of what

it means to be a thinking, speaking and perhaps even autonomous human being. The question of what - if anything - makes us different from animals was debated from numerous points of view: including talking dogs, philosophizing women, bestial men, humanlike beasts, and other creatures that defied the conventions of the time. This course explores some of the key literary texts that shaped this debate and pays careful attention to their cultural environments. Selected readings from Cervantes, La Fontaine, Swift, Rousseau, Buffon, Aikin, and Wollstonecraft, among others. Instructor: Holland.

Hum/En 29. Dream Narratives. *9 units (3-0-6); third term.* Dream narratives reveal as much about cultural beliefs and superstitions as they do about techniques of narration and interpretation. This course investigates key developments in the literature on dreams and dream interpretations with examples drawn from the Renaissance through the beginning of the nineteenth century. Selected readings from Boccaccio, Descartes, Calderón, Shakespeare, and Diderot, among others. Instructor: Holland.

Hum/En 33. Modern Metamorphoses. *9 units (3-0-6); second term.* Narratives of metamorphosis have traditionally used their dramatic subject matter—a radical change of form—as a vehicle for social criticism. This course explores the ways in which twentieth-century writers experiment with the concept of metamorphosis to take on the most pressing political and social issues of their day, including slavery, women's rights, and critiques of capitalist excess. Readings to include Kafka, Garnett, Orwell, Tawada, and Erpenbeck. Instructor: Holland. Not offered 2019–20.

Hum/En 35. 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. Not offered 2019–20.

655

Hum/En 36. 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. Not offered 2019–20.

Hum/En 37. 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. Not offered 2019–20.

Hum/En 38. Telling Time in American Modernism. *9 units (3-0-6); first term.* This course will explore modern American literature's interest in time. We will identify the narrative methods that modernist texts use to characterize the experience of lived time, or temporality, such as streams of consciousness, non-linear storytelling, and narrative omissions. What challenges do such methods pose to clock time and, more broadly, historical time? Students will learn about key literary movements within American modernism, and they will consider modernist literature's relationships to other genres and media, including music and visual culture. The course will emphasize modernism's engagements with shifting social norms related to race, class, gender, and sexuality during the first half of the twentieth century. Instructor: Sherazi.

Hum/En 39. Contemporary American Fiction. *9 units (3-0-6); first term.* This course will engage works of contemporary American fiction, with particular attention paid to experimental narrative strategies and their effects, including non-chronological storytelling, metafictionality, and narrative omissions. Notably, the literature we will read is set during and/or in the aftermath of World War II and/or the Vietnam War. How do the novel's central characters understand their roles in American society before, during, and beyond wartime? We will consider the ways in which social movements, including the civil rights and women's liberation movements, informed these works of fiction and how such literature resonates in our current moment. Authors/texts studied will include John Okada's No-No Boy (1957), Joan Didion's Democracy (1984), and Susan Choi's American Woman (2003). Instructor: Sherazi. Not offered 2019–20.

Hum/Pl 40. Right and Wrong. *9 units (3-0-6); first, second terms.* 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 psy-

chological 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. Instructor: Hay

Hum/Pl 41. Knowledge and Reality. *9 units (3-0-6); first, third terms.* 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, Hubert.

Hum/Pl 43. Meaning in Life. *9 units (3-0-6); first, second terms.* Experiencing one's life as meaningful is important for most people. Yet, what is it for a life to be meaningful? This course explores philosophical inquiries into meaning in life, examining such questions as, How does meaning in life relate to moral, epistemic, aesthetic, and hedonic final values in life? What does meaning in life imply regarding the metaphysics of value? What is the relation between meaning and welfare, achievement, and goal-directedness? What sort of activities, from work to leisure, can be sources of meaning in life? Drawing principally on recent work in analytic philosophy, the course will also examine whether scientific approaches, principally neuroscience and psychology, can illuminate the nature of meaning in life and will examine recent nihilistic challenges to meaning in life. Instructors: Quartz.

Hum/Pl 44. Philosophy Through Science Fiction. *9 units (3-0-6); third term.* This course will provide a broad introduction to philosophy using examples from science fiction to make abstract philosophical problems vivid. Topics may include: time travel and the reality of the past and future; teleportation and what makes someone the same person over time; fictional tales of extended deception and Cartesian skepticism; futuristic utopias and the question of what make a life good; the moral status of aliens and animals; intelligent robots and the relation between mind and body; parallel universes and the philosophical foundations of quantum physics. Instructor: Sebens.

657

Hum/Pl 45. Ethics & AI. *9 units (3-0-6); second term.* How do we reconcile the possibilities of modern machine learning with ethical

and moral demands of fairness, accountability and transparency? This course will take a case study based approach to the challenges at the interface of algorithms and human values. By exploring existing debates on algorithmic bias, explainable AI and data ownership, students will be exposed to the relevance of ethical systems of thought to modern social questions. Instructor: Eberhardt.

Hum/VC 49. Consuming Victorian Media. *9 units (3-0-6); first term.* Proliferating communication and entertainment media technologies in 19th-century England vexed the imagined boundaries between humans and machines while catalyzing social anxieties about aesthetics, attention, and distraction. We will explore both "old" (novels, paintings, sculptures) and "new" forms of 19th-century media (telegraphs, magic lanterns, and photography) as we analyze overly stimulating Gothic print media in Jane Austen's Northanger Abbey, Wordsworth's contempt for popular entertainments in The Prelude, and the inversion of imperial consumption in Bram Stoker's Dracula, a novel mediated through characters' telegrams, diary entries, and phonographic recordings. Authors studied also may include: Dickens, Christina Rossetti, Doyle, Kipling, and Vernon Lee. Instructor: Sullivan.

Hum/VC 50. Introduction to Film. *9 units (3-0-6); third term.* This course examines film as a technology, entertainment medium, and commercial art with an emphasis on American and European contexts. Students will acquire the basic vocabulary and techniques of film analysis, with an emphasis on style and structure, and develop an understanding of the historical development of film as both an art form and an industry from 1895 through the twentieth century. Topics covered include actualities and the birth of narrative film, silent film comedy, German expressionism, the Hollywood star system, Italian neo-realism, and the French New Wave. Instructor: Jurca.

Hum 75. Selected Topics in Humanities. *variable units; offered by announcement.* A course on a specialized topic in some area of the humanities, usually taught by new or visiting faculty. Recent offerings have included courses on film-making, poetry writing, speculative fiction, and the difference between humans and other animals. The course may be re-taken for credit except as noted in the course announcement. Class size is normally limited to 8 - 15 students. See registrar's announcement for details. Instructors: Staff, visitors.

Hum 80. Frontiers in the Humanities. *1 unit (1-0-0); third term.* Weekly seminar by a member of the Caltech humanities faculty or a visitor to discuss a topic of his or her current research at an introductory level. The course can be used to learn more about different areas of study within the humanities. For those interested in (or who become interested) in pursuing a second option in the humanities,

the course will introduce students to the kinds of research carried out by members of the humanities faculty and help them find faculty advisors. Instructors: Staff.

Hum 105 ab. Topics in French Culture and Literature. *9 units (3-0-6).* For course description, see L 105 ab.

Hum 114 abc. Spanish and Latin American Literature. *9 units (3-0-6).* For course description, see L 114 abc.

Hum 119. Selected Topics in Humanities. *variable; offered by announcement.* This is an advanced humanities course on a specialized topic in some area of the humanities. It is usually taught by new or visiting faculty. The course may be re-taken for credit except as noted in the course announcement. Limited to 15 students. See registrar's announcement for details. Instructors: Staff, visitors.

L/Hum 150 a. Japanese Literature in Translation. *9 units (3-0-6).* For course description, see Languages.

L/Hum 150 b. Japanese Literature in Translation. *9 units (3-0-6).* For course description, see Languages.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6).* 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. Advanced Chinese II: Topics in Chinese Literature. *9 units (3-0-6).* For course description, see L 174.

HPS/H 180. Forbidden Knowledge. *9 units (3-0-6); first term.* For course description, see History and Philosophy of Science.

INFORMATION AND DATA SCIENCES

IDS 9. Introduction to Information and Data Systems Research. *1 unit (1-0-0); second term.* This course will introduce students to research areas in IDS through weekly overview talks by Caltech faculty and aimed at first-year undergraduates. Others may wish to take the course to gain an understanding of the scope of research in computer science. Graded pass/fail. Not offered 2019–20.

ACM/IDS 101 ab. Methods of Applied Mathematics. *12 units (4-4-4).* For course description, see Applied and Computational Mathematics.

ACM/IDS 104. Applied Linear Algebra. *9 units (3-1-5).* For course description, see Applied and Computational Mathematics.

CMS/ACM/IDS 107. Linear Analysis with Applications. *12 units (3-3-6).* For course description, see Computing and Mathematical Sciences.

CMS/ACM/IDS 113. Mathematical Optimization. *12 units (3-0-9).* For course description, see Computing and Mathematical Sciences.

ACM/EE/IDS 116. Introduction to Probability Models. *9 units (3-1-5).* For course description, see Applied and Computational Mathematics.

CS/IDS 121. Relational Databases. *9 units (3-0-6).* For course description, see Computer Science.

EE/Ma/CS/IDS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ma/CS/IDS 136. Topics in Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

CMS/CS/IDS 139. Analysis and Design of Algorithms. *12 units (3-0-9).* For course description, see Computation and Mathematical Sciences.

CS/IDS 142. Distributed Computing. *9 units (3-0-6).* For course description, see Computer Science.

CS/EE/IDS 143. Communication Networks. *9 units (3-3-3).* For course description, see Computer Science.

Ma/ACM/IDS 140 ab. Probability. *9 units (3-0-6); second, third terms.* For course description, see Mathematics.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. *12 units (3-4-5).* For course description, see Computing and Mathematical Sciences.

CS/IDS 150 ab. Probability and Algorithms. *9 units (3-0-6).* For course description, see Computer Science.

CS/IDS 153. Current Topics in Theoretical Computer Science. *9 units (3-0-6).* For course description, see Computer Science.

ACM/IDS 154. Inverse Problems and Data Assimilation. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

CMS/CS/CNS/EE/IDS 155. Machine Learning & Data Mining. *12 units (3-3-6).* For course description, see Computing and Mathematical Sciences.

IDS/ACM/CS 157. Statistical Inference. *9 units (3-2-4); third term. Prerequisites: ACM/EE/IDS 116, Ma 3.* Statistical Inference is a branch of mathematical engineering that studies ways of extracting reliable information from limited data for learning, prediction, and decision making in the presence of uncertainty. This is an introductory course on statistical inference. The main goals are: develop statistical thinking and intuitive feel for the subject; introduce the most fundamental ideas, concepts, and methods of statistical inference; and explain how and why they work, and when they don't. Topics covered include summarizing data, fundamentals of survey sampling, statistical functionals, jackknife, bootstrap, methods of moments and maximum likelihood, hypothesis testing, p-values, the Wald, Student's t-, permutation, and likelihood ratio tests, multiple testing, scatterplots, simple linear regression, ordinary least squares, interval estimation, prediction, graphical residual analysis. Instructor: Zuev.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. *9 units (3-3-3); third term. Prerequisites: Ma 3 or ACM/EE/IDS 116, IDS/ACM/CS 157.* The main goal of the course is to provide an introduction to the central concepts and core methods of statistical learning, an interdisciplinary field at the intersection of statistics, machine learning, information and data sciences. The course focuses on the mathematics and statistics of methods developed for learning from data. Students will learn what methods for statistical learning exist, how and why they work (not just what tasks they solve and in what built-in functions they are implemented), and when they are expected to perform poorly. The course is oriented for upper level undergraduate students in IDS, ACM, and CS and graduate students from other disciplines who have sufficient background in probability and statistics. The course can be viewed as a statistical analog of CMS/CS/CNS/EE/IDS 155. Topics covered include supervised and unsupervised learning, regression and classification problems, linear regression, subset selection, shrinkage methods, logistic regression, linear discriminant analysis, resampling techniques, tree-based methods, support-vector machines, and clustering methods. Instructor: Zuev.

CS/CNS/EE/IDS 159. Advanced Topics in Machine Learning. *9 units (3-0-6).* For course description, see Computer Science.

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/IDS 162. Data, Algorithms and Society. *9 units (3-0-6).* For course description, see Computer Science.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. *12 units (3-3-6).* For course description, see Computer Science.

EE/CS/IDS 167. Introduction to Data Compression and Storage. *9 units (3-0-6).* For course description, see Electrical Engineering.

ACM/EE/IDS 170. Mathematics of Signal Processing. *12 units (3-0-9).* For course description, see Applied and Computational Mathematics.

CS/IDS 178. Numerical Algorithms and their Implementation. *9 units (3-3-3).* For course description, see Computer Science.

IDS 197. Undergraduate Reading in the Information and Data Sciences. *Units are assigned in accordance with work accomplished; first, second, third terms. Prerequisites: Consent of supervisor is required before registering.* Supervised reading in the information and data sciences 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.

IDS 198. Undergraduate Projects in Information and Data Sciences. *Units are assigned in accordance with work accomplished; first, second, third terms. Prerequisites: Consent of supervisor is required before registering.* Supervised research in the information and data sciences. The topic must be approved by the project supervisor and a formal report must be presented upon completion of the research. Graded pass/fail. Instructor: Staff.

IDS 199. Undergraduate thesis in the Information and Data Sciences. *9 units (1-0-8); first, second, third terms. Prerequisites: 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 faculty member and approved by the option representative. Projects must include significant design effort and a written Report is required. Open only to upperclass students. Not offered on a pass/fail basis. Instructor: Staff.

ACM/IDS 204. Topics in Linear Algebra and Convexity. *12 units (3-0-9).* For course description, see Applied and Computational Mathematics.

ACM/IDS 213. Topics in Optimization. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

ACM/IDS 216. Markov Chains, Discrete Stochastic Processes and Applications. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

ACM/EE/IDS 217. Advanced Topics in Stochastic Analysis. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

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. Not offered 2019–20. Instructor: Bruck.

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 305–306 for complete details.

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 2019–20.

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. T*he 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: Merrill, Orcel.

L 104. French Cinema. *9 units (3-0-6); first term; Offered concurrently with VC 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 VC 104, which satisfies the advanced humanities requirement. Instructor: Orcel. Not offered 2019–20.

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. Instructor: Orcel. Not offered 2019–20.

L 106 abc. Elementary Japanese. *9 units (4-0-5); 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: Fujio.

L 107 abc. Intermediate Japanese. *9 units (3-0-6); first, second, third terms. Prerequisites: 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. Instructor: Hirai.

L 108 abc. Advanced Japanese. *9 units (3-0-6); first, second terms. Prerequisites: 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. Instructor: Hirai.

L/VC 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 Melies and the Lumiere 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: Arjona, Garcia.

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: 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. Instructor: 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 139. Translation Theory and Practice (Chinese Historical Sources Seminar). *9 units (3-0-6); first term.* This seminar will introduce students to the problems and practices of historical translation for academic purposes, with a focus on primary materials from Chinese history. Students will take responsibility for an individual translation project, participate in seminar discussions and collaborative projects to improve the translations being made, and discuss the philosophical and methodological questions at the heart of the practice of translation. Advanced proficiency in written Chinese is required. Students who write analyses (4,000 words) of the sources being translated may enroll in this class as H 139, which satisfies the advanced humanities credit. Instructor: Dykstra. Not offered 2019–20.

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 2019–20.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6).* For course description, see History.

L/Hum 150 a. Japanese Literature in Translation. *9 units (3-0-6); third term.* Read and examine the selected classical Japanese literature and its traditions from 7th to 11th century from the perspectives of women, anti-heroes, and religions. A comparative analysis is applied to many genres such as oral traditions, performing arts, films, picture scrolls, comics, and anime to understand

how Japanese think, and how Shinto and Buddhism have formed their ways of life, ethics, and concepts of life and death. Read selected portions of "The Kojiki", "Manyoshu", "The Tale of Ise", "The tale of the Bamboo-Cutter" (The Tale of the Moon Princess), and "The Tale of Genji." Instructor: Hirai.

L/Hum 150 b. Japanese Literature in Translation. *9 units (3-0-6); third term.Read and examine the selected Medieval to premodern Japanese literature and its traditions from 11th to 18th century from the perspectives of women, anti-heroes, and religions.* A comparative analysis is applied to many genres such as oral traditions, performing arts, films, picture scrolls, comics, and anime to understand how Japanese think, and how Shinto, Buddhism, Neo-Confucianism, as well as the social systems, have formed their ways of life, ethics, and concepts of life and death. Read "The Princess Who Loved Insects" from "The Tsutsumi-Chunagon Monogatari", selected chapters of "The Tale of The Heike", "The Konjyaku Monogatari", and "Otogizoshi". Also read "The Double Suicide at Sonezaki" and "The Double Suicide at Amijima." Instructor: Hirai. Not offered 2019–20.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); third 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. Instructor: Merrill.

L/VC 153. Refugees and Migrants' Visual and Textual Representations. *9 units (3-0-6); second term.* This course focuses on the refugees and migrants' images in documentaries, narrative films, graphic novels, fictional texts, poetic works, and autobiographical narratives. It investigates how these representations participate in the development and strengthening of political discourse. Works by authors such as Hannah Arendt, Antje Ellermann, Achille Mbembe, Martin A. Schain, and Sasha Polakow-Suransky will provide some context to our analysis. Topics discussed in class include the historical and economic relationships of Europe with the refugees and migrants' countries of origin, the rise of anti-immigrant politics and its significance for the future of the European Union, but also its impact on social peace, in France in particular. This course is taught in English. Instructor: Orcel.

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. Not offered 2019–20.

L 167. Latin Literature. *9 units (3-0-6); second term. Prerequisites: 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. *9 units (3-0-6); 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 (3-0-6); 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. *9 units (3-0-6); 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. *9 units (3-0-6); 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. Advanced Chinese II: 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. Instructor: 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. Law and Economics. *9 units (3-0-6); third term.* This is a law and economics course that studies the economic rationale for different legal principles, using environmental regulations as leading examples. In situations where free markets produce inefficient outcomes, we wish to understand what types of constraints a government can impose on markets so as to restore efficiency. Topics we will cover include resolution of externalities via market and non-market solutions, problems of the commons and anti-commons, and contracting under incomplete information. Instructor: Schenone.

Pl/Law 99. Causation and Responsibility. *9 units (3-0-6).* For course description, see Philosophy.

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 mate-

rials 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: Hofmann.

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 (1-0-0); first, second, third terms.* A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructors: Bernardi, Faber, Fultz.

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, defects, thermodynamics, phase equilibria, microstructure, and properties are described. Instructor: 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, architecture, defects, and mechanical properties. Elastic, inelastic, and plastic properties of crystalline and amorphous materials. Relations between stress and strains for different types of materials. Introduction to dislocation theory, motion and forces on dislocations, strengthening mechanisms in crystalline solids. Nanomaterials: properties, fabrication, and mechanics. Architected solids: fabrication, deformation, failure, and energy absorption. Biomaterials: mechanical properties of composites, multi-scale microstructure,

biological vs. synthetic, shear lag model. Fracture in brittle solids and linear elastic fracture mechanics. Instructor: Greer.

MS 121. Laboratory Research Methods in Materials Science.
9 units (1-4-4); second term. Prerequisites: MS 115 or graduate standing. Introduction to experimental methods and approaches for the analysis of structure, dynamics, and properties of materials. Staff members with expertise in various areas including mechanical testing, calorimetry, X-ray diffraction, scanning and transmission electron microscopy, solid state NMR and electrochemistry will introduce and supervise experiments in their specialty. As the situation permits, students are given a choice in selecting experiments. Instructor: Ahn.

MS/APh 122. Diffraction, Imaging, and Structure. *9 units (0-4-5); first term. 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. Instructor: Ahn.

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: Staff. Not offered 2019–20.

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. Instructor: Bernardi.

671

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. Instructor: 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. Instructors: Greer/Kornfield.

MS 141. Introduction to Computational Methods for Science and Engineering. *9 units (3-0-6); third term. Prerequisites: graduate standing or instructor's permission.* An introduction to basic methods and code development tools for scientific computing in the Python language, including coding and visualization. Topics include: introduction to Python and its packages Matplotlib, Numpy and SciPy. Numerical precision and sources of error. Root-finding and optimization. Numerical differentiation and integration. Discrete Fourier transforms. Numerical methods for ordinary differential equations. Finite-difference methods for partial differential equations. Introduction to numerical methods for solving linear systems and eigenvalue problems. If time permits: selected topics on data analysis with NumPy, Pandas and Matplotlib. Students will develop numerical calculations in the homework and in a final project. Instructor: Bernardi.

MS 142. Application of Diffraction Techniques in Materials Science. *9 units (2-3-4); second term. Prerequisite: 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. Not offered 2019–20.

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 2019–20.

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. Instructor: Faber.

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.

APh/MS 256. Computational Solid State Physics and Materials Science. *9 units (3-3-3); third term.* For course description, see Applied Physics.

ME/MS 260. Micromechanics. *9 units (3-0-6).* 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: Ramakrishnan, Gekhtman, Kechris, Makarov, Flach, Ni.

Ma 1 d. Series. *4 units (2-0-2); second term only. Prerequisites: 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: Rains.

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: Wang, Frank.

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 horse-shoe map. Instructor: Parikh.

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. Instructors: Flach, Campbell, Mantovan.

Ma/CS 6/106 abc. Introduction to Discrete Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisites: 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: Conlon, Shikhelman, Kechris.

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 $a2 — db2 = ±1$, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Xu.

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: Rains.

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: Flach.

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: Ni.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. *6 units (2-0-4); third term.* For course description, see Freshman Seminars.

Ma 13. Problem Solving in Vector Calculus. *2 units (2-0-0); second term. Prerequisites: Concurrent registration in Ph 1b.* A two-hour per week, hands-on class for those students enrolled in Ph 1b needing extra practice with problem solving in vector calculus. Instructor: Rains.

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: Rains.

Ma 20. Frontiers in Mathematics. *1 unit (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. Instructor: Flach.

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 97. Research in Mathematics. *Units to be arranged in accordance with work accomplished.* This course is designed to allow students to continue or expand summer research projects and to work on new projects. Students registering for more than 6 units of Ma 97 must submit a brief (no more than 3 pages) written report outlining the work completed to the undergraduate option rep at the end of the term. Approval from the research supervisor and student's advisor must be granted prior to registration. Graded pass/fail.

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 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: Lazebnik, Durcik, Makarov.

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: Markovic, Gekhtman, Chen.

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 dis-

tributions 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: Angelopoulos, Rains, Durcik.

Ma 111 abc. 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, Painleve transcendents and/or elliptic analogues Instructors: Cuenca, Radziwill, Lazebnik.

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 2019–20.

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: Panagiotopolous.

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 2019–20.

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 2019–20.

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, semisimple algebras, Weddburn theorems, Jacobson radicals, representation theory of finite groups. Instructors: Ramakrishnan, Zhu, Graber.

Ma 121 ab. Combinatorial Analysis. *9 units (3-0-6); second, third 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: Tyomkyn, Conlon.

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

679

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 2019–20.

Ma 124. Elliptic Curves. *9 units (3-0-6); second 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 2019–20.

Ma 125. Algebraic Curves. *9 units (3-0-6); third term. 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 2019–20.

EE/Ma/CS 126 ab. Information Theory. *9 units (3-0-6); first, second terms.* For course description, see Electrical Engineering.

EE/Ma/CS/IDS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

Ma 128. Homological Algebra. *9 units (3-0-6); second term. Prerequisites: Math 120 abc or instructor's permission.* This course introduces standard concepts and techniques in homological algebra. Topics will include Abelian and additive categories; Chain complexes, homotopies and the homotopy category; Derived functors; Yoneda extension and its ring structure; Homological dimension and Koszul complexe; Spectral sequences; Triangulated categories, and the derived category. Instructor: Zhu.

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. Instructors: Kivinen, Xu, Campbell.

Ma 132 abc. Topics in Algebraic Geometry. *9 units (3-0-6). Prerequisites: Ma 130 or instructor's permission.* This course will cover advanced topics in algebraic geometry that will vary from year to year. Topics will be listed on the math option website prior to the

start of classes. Previous topics have included geometric invariant theory, moduli of curves, logarithmic geometry, Hodge theory, and toric varieties. This course can be repeated for credit. Not offered 2019-20.

Ma 135 ab. Arithmetic Geometry. *9 units (3-0-6); first term. 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 2019–20.

EE/Ma/CS/IDS 136. Topics in Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

Ma/ACM/IDS 140 ab. Probability. *9 units (3-0-6); second, third terms. Prerequisites: For 140 a, Ma 108 b is strongly recommended.* 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. Instructor: Tamuz, Ouimet.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6); third 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: Isett.

Ma 145 abc. Topics in Representation Theory. *9 units (3-0-6); second, third terms. Prerequisites: Ma 5.* This course will discuss the study of representations of a group (or related algebra) by linear transformations of a vector space. Topics will vary from year to year, and may include modular representation theory (representations of finite groups in finite characteristic), complex representations of specific families of groups (esp. the symmetric group) and unitary representations (and structure theory) of compact groups. Part a not offered in 2019–20. Instructors: Kivinen, Cuenca.

Ma 147 abc. Dynamical Systems. *9 units (3-0-6); first, second terms. Prerequisites: Ma 108, Ma 109, or equivalent.* First term: real dynamics and ergodic theory. Second term: Hamiltonian dynamics. Third term: complex dynamics. Part c not offered in 2019–20. Instructors: Radziwill, Lazebnik.

Ma 148 ab. Topics in Mathematical Physics. *9 units (3-0-6); second and third terms.* This course covers a range of topics in math-

ematical 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. Geometric theory of quantum information and quantum entanglement based on information geometry and entropy. Instructors: Parikh, Makarov.

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: Markovic, Ni, Chen.

Ma 157 abc. 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. Part c not offered in 2019–20. Instructor: Smillie.

Ma 160 abc. Number Theory. *9 units (3-0-6); first, second terms. Prerequisites: 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. Part c not offered in 2019–20. Instructors: Burungale, Campbell.

Ma 162 ab. Topics in Number Theory. *9 units (3-0-6); first, second term. 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. Instructor: Frank, Burungale.

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. Instructors: Chen, Kechris, Smillie, Zhu, Durcik, Shikhelman, Angelopoulos, Frank, Wang, Tyomkyn, Xu, Isett, Demirel-Frank.

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 10. Thinking Like an Engineer. *1 unit; first term.* A series of weekly seminars by practicing engineers in industry and academia to introduce students to principles and techniques useful for Mechanical Engineering. The course can be used to learn more about the different areas of study within mechanical engineering. Topics will be presented at an informal, introductory level. Required for ME undergraduates. Graded pass/fail. Instructor: Andrade.

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; momen-

tum 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, Daraio, Asimaki.

ME 13/113. 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. 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 (CAD) 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 manual 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. Instructor: Van Deusen.

ME 14. Design and Fabrication. *9 units (3-5-1); third term. Prerequisites: ME 12ab, ME 13.* Enrollment is limited and is 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 23/123. CNC Machining. *4 units (0-4-0); third, summer terms. Prerequisites: ME 13/113.* Enrollment is limited and is based on responses to a questionnaire available in the Registrar's office. Introduction to computer numerical control machining. Students will learn to create Gcode and Mcode using Computer-Aided Manufacturing (CAM) software; they will be instructed on how to safely prepare and operate the machine's functions; and will be taught how

to implement programmed data into several different types of CNC equipment. The class will cover the parts and terminology of the equipment, fixturing materials, setting workpiece, and tool offsets. Weekly assignments will include the use of CAM software, machine operation demonstrations, and machining projects. Instructor: Staff.

ME 40. Dimensional and Data Analyses in Engineering. *9 units (3-0-6); first term. Prerequisites: Ma 1 abc.* The first part of this course covers the application of symmetry and dimensional homogeneity (Buckingham Pi theorem) to engineering analysis of systems. The important role of dimensional analysis in developing empirical theories, designing experiments and computer models, and analyzing data are stressed. The second part of the course focuses on quantitative data analysis including linear regression, least-squares, principle components, Fourier analysis, and Bayesian methods. The underlying theory is briefly covered, but the focus is on application to real-world problems encountered by mechanical engineers. Applications to uncertainty analysis and quantification are discussed. Homework will include implementation of techniques in Matlab. First offered 2020-21. Instructor: Colonius.

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 ACM 11.* Two-quarter course sequence covers the general theory and methods of computational fluid dynamics (CFD) and finite element analysis (FEA) with experimental laboratory methods applied to complementary engineering problems in solid, structural, and fluid mechanics. Computational procedures are discussed and applied to the analysis of steady-state, transient, and dynamic problems using a commercial software. CFD and FEA topics covered include meshing, types of elements, steady and unsteady solvers, inviscid and viscous flow, internal and external flow, drag and lift, static and dynamic mechanical loading, elastic and plastic behavior, and vibrational (modal) analysis. Fluid mechanics laboratory experiments introduce students to the operation of a water tunnel combined with laser particle image velocimetry (PIV) for quantified flow field visualization of velocity and vorticity. Solid mechanics experiments introduce students to the operation of a mechanical (axial/torsional) load frame combined with digital image correlation (DIC) and strain gage transducers for quantification and full field visualization of displacement and strain. Technical writing skills are emphasized through the generation of detailed full-length lab reports using a scientific journal format. Instructor: Mello.

ME 72 ab. Engineering Design Laboratory. *9 units (3-4-2) first term; (1-8-0) second term. Prerequisites: ME 14.* 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 EAS option. Not offered on a pass/fail basis. Instructors: Mello, Van Deusen.

CS/EE/ME 75 abc. 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 and third terms.* 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: Minnich.

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/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); second, third terms.* For course description, see Engineering.

ME/EE/EST 109. Energy Technology and Policy. *9 units (3-0-6); first term. Prerequisites: Ph 1 abc, Ch 1 ab and Ma 1 abc.* Energy technologies and the impact of government policy. Fossil fuels, nuclear power, and renewables for electricity production and transportation. Resource models and climate change policies. New and emerging technologies. Instructor: Blanquart.

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. Not offered 2019–20.

MS/ME/MedE 116. Mechanical Behavior of Materials. *9 units (3-0-6).* For course description, see Materials Science.

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); second, third 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. Not offered 2019–20.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6).* For course description, see Aerospace.

ME/CS/EE 129. Experimental Robotics. *9 units (3-6-0); first term.* This course covers the foundations of experimental realization on robotic systems. This includes software infrastructures, e.g., robotic operating systems (ROS), sensor integration, and implementation on hardware platforms. The ideas developed will be integrated onto robotic systems and tested experimentally in the context of class projects. Instructor: Staff.

ME/CS/EE 133 abc. Robotics. *9 units (3-3-3); first, second, third terms. Prerequisites: ME/CS/EE 129, may be taken concurrently, or with permission of instructor.* 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 dexterous manipulation using multifingered hands, and advanced obstacle avoidance and motion planning algorithms. Additional topics include robotics research in the area of autonomous navigation and vision. Including 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 2019–20.

ME/CS/EE 134. Robotic Systems. *9 units (3-6-0); second term. Prerequisites: ME/CS/EE 129, may be taken concurrently, or with permission of instructor.* This course covers the basics of robotic systems at the intersection of computer vision, machine learning and control. It includes selected topics from each of these domains, and their integration points. The lectures will be accompanied by a project that will integrate these ideas on hardware, including building a custom robotic, with the end result being a final demonstration of the concepts studied in the course. Instructor: Staff.

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); third 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. Not offered 2019–20.

AM/ME 165. Finite 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, visco-elasticity, viscoplasticity, creep, damage, friction, failure mechanisms, shear localization, and interaction of deformation processes with fluids. Engineering and geological applications. Not offered 2019–20.

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); first, third terms.* The faculty will prepare courses on advanced topics to meet the needs of graduate students. Instructor: Minnich.

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 2019–20.

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 ab. Computational Solid Mechanics. *9 units (3-5-1).* 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. *9 units (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/Ge 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.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. *9 units (2-1-6).* For course description, see Applied Mechanics.

ME/MS 260. Micromechanics. *9 units (3-0-6); third term. 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 2019–20.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6).* For course description, see Aerospace.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6); third term. 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. Instructor: Lapusta.

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. Instructors: Gao, Tai and Wang.

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: An overview of the physiology of a system followed by examples of current clinical medical challenges and research highlighting diagnostic and therapeutic modalities. The final three 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 description, see Engineering.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6).* For course description, see Chemical Engineering.

EE/MedE 114 ab. Analog Circuits Design. *12 units (4-0-8).* For course description, see Electrical Engineering.

EE/MedE 115. Micro-/Nano-scales Electro-optics. *9 units (3-0-6).* 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).* For course description, see Electrical Engineering.

EE/CS/MedE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0).* For course description, see Electrical Engineering.

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. *9 units (4-0-5) each; parts a and b are taught in second and third terms in odd academic years starting 2019–20 and part c is taught in second term in even academic years starting 2020-21. Prerequisites: instructor's permission.* Part a covers the principles of optical photon transport in biological tissue. Topics include a brief introduction to biomedical optics, single-scatterer theories, Monte Carlo modeling of photon transport, convolution for broad-beam responses, radiative transfer equation and diffusion theory, hybrid Monte Carlo method and diffusion theory, and sensing of optical properties and spectroscopy, (absorption, elastic scattering, Raman scattering, and fluorescence). Part b covers established optical imaging technologies. Topics include ballistic imaging (confocal microscopy, two-photon microscopy, super-resolution microscopy, etc.), optical coherence tomography, Mueller optical coherence tomography, and diffuse optical tomography. Part c covers emerging optical imaging technologies. Topics include photoacoustic tomography, ultrasound-modulated optical tomography, optical time reversal (wavefront shaping/engineering), and ultrafast imaging. Instructor: Wang.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. *9 units (3-6-0).* For course description, see Electrical Engineering.

EE/BE/MedE 185. MEMS Technology and Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/MedE 187. VLSI and ULSI Technology. *9 units (3-0-6).* 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. *189 a, 12 units (3-6-3) offered both first and third terms.* 189b, 9 units (0-9-0) offered only third term. 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 201 ab. 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 and Gao.

MedE 202. Sensors in Medicine. *9 units (3-0-6); second term. Prerequisites: None.* Sensors play a very important role in all aspect of modern life. This course is an essential introduction to a variety of physical, chemical and biological sensors that are used in medicine and healthcare. The fundamental recognition mechanisms, transduction principles and materials considerations for designing powerful sensing and biosensing devices will be covered. We will also discuss the development of emerging electronic-skin, wearable and soft electronics toward personalized health monitoring. Participants in the course will develop proposals for novel sensing technologies to address the current medical needs. Instructor: Gao.

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. These technologies have been originally and mainly developed for space exploration. Spinoff applications to medicine have been explored and proven with various degrees of success and maturity. This class introduces these topics, the basics of the technologies, their intended original space applications, and the medical applications. Topics include but are not limited to multimodal imaging, UV/Visible/NIR imaging, imaging spectrometry, sensors, robotics, and navigation. Graded pass/fail. Instructor: Nikzad.

MedE/BE/Ae 243. Physiological Mechanics. *9 units (3-0-6); second term. Prerequisites: 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. Low and High Reynolds number locomotion. Instructor: TBD/

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 51. 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 55. The Great Orchestras: Their History, Conductors and Repertoire. *9 units (3-0-6); third term.* This survey course will trace the symphony orchestra from its origins in the mid eighteenth century to the present day. Special emphasis will be given to the great civic orchestras of the nineteenth and twentieth centuries, their conductors, and 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. Instructor: Neenan.

Mu 56. Jazz History. *9 units (3-0-6); second 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. Instructor: Neenan.

Mu 57. 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. Not offered 2019–20.

Mu 58. Harmony I. *9 units (3-0-6), second term. Prerequisite: Mu 57 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. Not offered 2019–20.

Mu 59. Harmony II. *9 units (3-0-6), third term. Prerequisite: Mu 58 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. Not offered 2019–20.

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. Instructor: Neenan.

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.

NEUROBIOLOGY

Bi/CNS/NB/Psy 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS/NB 154. Principles of Neuroscience. *9 units (3-0-6).* For course description, see Biology.

Bi/NB/BE 155. Neuropharmacology. *6 units (3-0-3).* For course description, see Biology.

Bi/CNS/NB 157. Comparative Nervous Systems. *9 units (2-3-4).* For course description, see Biology.

Pl/CNS/NB/Bi/Psy 161. Consciousness. *9 units (3-0-6).* For course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-4-6).* For course description, see Biology.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. *6 (3-0-3); second term. Prerequisites: Bi/CNS/NB/Psy 150 or instructor's permission.* The neuroscience of psychiatric, neurological, and neurodegenerative disorders and of substance abuse, in humans and in animal models. Students master the biological principles including genetics, cell biology, biochemistry, physiology, and circuits. Topics are taught at the research level and include classical and emerging therapeutic approaches and diagnostic strategies. Instructors: Lester, Lois. Given in alternate years; offered 2019–20.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3-0-6). Prerequisites: Bi/CNS/NB/Psy 150 or equivalent.* For course description, see Biology.

CNS/Bi/Psy/NB 176. Cognition. *9 units (4-0-5); third term.* For course description, see Computation and Neural Systems.

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 units (2-0-4).* For course description, see Biology.

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/CNS/NB 195. Mathematics in Biology. *9 units (3-0-6).* For course description, see Biology.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. *6 units.* For course description, see Bioengineering.

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).* For course description, see Biology.

CNS/Bi/NB 247. Cerebral Cortex. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi/CNS/NB 250 c. 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).* For course description, see Computation and Neural Systems.

697

NB 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

PERFORMING AND VISUAL ARTS

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.

PVA 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.

PVA 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. Section 2: Piano four-hands. Section 3: Guitar ensemble. Instructors: Jasper White, Ward, Elgart.

PVA 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: Price.

PVA 33 abc. Wind Orchestra. *3 units (0-3-0); first, second, third terms.* The Caltech-Occidental Wind Orchestra is comprised of students, faculty, staff, and alumni from Caltech and Occidental College. The ensemble rehearses Thursday nights from 7:30-9:45 pm. and performs three programs per year (one per term) at Ramo Auditorium and Thorne Hall. Repertoire is comprised of traditional and contemporary music encompassing a wide variety of styles, and regularly features renowned guest artists. Open to students of all levels of previous experience. Instructor: Price.

PVA 34 abc. Jazz Band/Jazz Improvisation. *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, with additional opportunity for the study of improvisation. Class meets one evening per week.Instructor: Catlin.

PVA 35 abc. Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of choral repertoire spanning a range of historical periods and musical styles. Includes occasional collaborative performances with the orchestra. No previous experience required. Three hours a week. Instructor: Sulahian.

PVA 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.

PVA 40 a. Find Your Stories. *3 units (2-0-1); first term.* Through a series of writing exercises, improvisation, and performance/vocal techniques, students will explore/discover/write new narratives for the ever-changing 21st century global landscape. The class culminates in public presentations recorded in front of a live audience. Instructor: Brophy.

PVA 40 b. Moth to the Flame. *3 units (2-0-1); first term.;* second term. This second term emphasizes the relation of the speaker with community. In multiple five minute presentations covering selected topics, students will condense their stories to communicate complex social/scientific narratives and practice how scientists deal with citizen science and democracy in open forums. Lecturers from other Divisions will discuss their own history of public speaking and share their process on how they construct, justify and arrive at their scientific explanations. Instructor: Brophy.

PVA 40 c. Long Form Storytelling. *3 units (2-0-1); first term.;* third term. This final term combines the various narratives compiled over previous terms and weaves them into a long-form storytelling narrative for a live invited audience at the conclusion. Students receive public speaking experience and end the year with a forum to share their process and their science stories with an invited audience. Efforts will be made to coordinate the event with outside opportunities such as existing TedX or Moth events. Instructor: Brophy.

PVA 41 abc. Storytelling for Scientists. *3 units (2-0-1); first, second, third terms.* To be effective leaders and communicators, scientists need to explain/perform their science. Through a series of writing exercises, performance/vocal techniques with new media, students explore/write and perform new narratives for the ever-changing 21st century global landscape. The final class culminates in original stories recorded in front of a live audience. May be repeated for credit. Instructors: Brophy.

699

PVA 42 abc. Improvisation for Scientists. *3 units (2-0-1); first, second, third terms.* This class is taught sequentially over the academic year and begins with rudimentary improvisation techniques, and continues in the winter/spring with professional improvisation guidance, long form improvisation, and advanced techniques with monthly public performances. Instructors: Brophy.

PVA 61 abc. Silkscreen and Silk Painting. *3 units (0-3-0); first, second, third terms.* Instruction in silkscreening techniques, primar-

ily for T-shirts. Progressive development of silk painting skills for fine art. Instructor: Barry.

PVA 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.

PVA 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.

PHILOSOPHY

Hum/Pl 40. Right and Wrong. *9 units (3-0-6).* For course description, see Humanities.

Hum/Pl 41. Knowledge and Reality. *9 units (3-0-6).* For course description, see Humanities.

Hum/Pl 43. Meaning In Life. *9 units (3-0-6).* For course description, see Humanities.

Hum/Pl 44. Philosophy Through Science Fiction. *9 units (3-0-6).* For course description, see Humanities.

Hum/Pl 45. Ethics & AI. *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); third 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 2019–20.

Pl 100. Free Will. *9 units (3-0-6); second 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. Instructor: Hitchcock.

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6); offered by announcement. Prerequisite: Hum/Pl 40 or Hum/Pl 41 or instructor's permission.*

HPS/Pl/CS 110. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 120. Introduction to Philosophy of Science. *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); 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).* 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 136. Happiness and the Good Life. *9 units (3-0-6).* 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/CNS/NB/Bi/Psy 161. Consciousness. *9 units (3-0-6); third term. Prerequisites: None, but strongly suggest prior background in philosophy of mind and basic neurobiology (such as Bi150).* One of the last great challenges to our understanding of the world concerns conscious experience. What exactly is it? How is it caused or constituted? And how does it connect with the rest of our science? This course will cover philosophy of mind, cognitive psychology, and cognitive neuroscience in a mixture of lectures and in-class discussion. There are no formal pre-requisites, but background in philosophy (equivalent to Pl41, Pl110) and in neuroscience (equivalent to BI/CNS 150) is strongly recommended and students with such background will be preferentially considered. Limited to 20. Instructors: Eberhardt, Adolphs.

HPS/Pl 165. Selected Topics in Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

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 2019–20.

PHYSICAL EDUCATION

PE 1. Student Designed Fitness. *3 units; first and 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. Instructor: Staff.

PE 2. Healthier Living. *3 units.* 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 accommodate travel off campus. Instructor: Staff.

PE 4. Introduction to Power Walking. *3 units.* 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. *3 units; first term.* Students will learn fundamental principles of sound running training to help with short-term and long-term improvement. The course will cover workout design, running mechanics, injury prevention and other related topics. The course can accommodate a wide range of abilities and experience levels, from beginner to intermediate. Course assessments will include fitness tests to gauge improvement and written work on running-related topics. Instructors: Staff.

PE 6. Core Training, Beginning/Intermediate. *3 units.* 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.* 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; first 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 11. Rollerblading. *3 units.* Students will learn the fundamentals of skating safely. We will focus on getting you rolling, turning and maneuvering and teaching you to master the heel brake stop, safely! You will be able to skate, stop and turn so that you can enjoy skating as part of your aerobic and muscular fitness routine. Basic elements of fitness will be taught and incorporated such as stretching, balance, core strength and other components of general fitness such as heart rate monitoring and conditioning. Field trips may be a part of this course. Bringing your own equipment is recommended but see instructor for assistance, some equipment will be provided. Instructors: Staff.

PE 14. Basketball Skills, Beginning and 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. *3 units.* Beginning fencing includes basic techniques of attack, defense, and counter-offense. Lecture topics include fencing history, strategy, scouting and analysis of opponents, and gamesmanship. 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. Frisbee Golf. *3 units; second term.* This course is designed to provide students an opportunity to learn various disc golf shots (driving, mid-range, putting), strategies, rules, and etiquette. Class time will be used practicing on campus and playing the game at various local courses. Students will develop the knowledge and ability to play disc golf confidently on a recreational basis. Instructor: Staff.

PE 28. Flying Saucers. *3 units.* 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 29. Outdoor Lawn Games. *3 units; third term.* Students will participate in 5 specifically chosen strategic games (Inner Tube Water Polo, Dodgeball, Bocce, Corn Hole, Flag Football) and learn basic strategy and rules, fitness and health components as well as learning how to compete in cooperative team games. Course requirements include great attitude, attendance and effort of having fun and trying something new while working on your coordination and general fitness. Instructors: Staff.

PE 30. Golf, Beginning and Intermediate. *3 units; first term.* 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. Instructors: Staff.

PE 31. Indoor/Outdoor Cycling. *3 units; second term.* During this introductory course students will utilize both indoor cycling and outdoor cycling as a tool for fitness and fun. 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 and helmet however equipment will be provided as needed. Please see instructor. Instructors: Staff.

PE 33. Beginning Triathlon Training. *3 units; third 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; third 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 and Intermediate. *3 units; first, second, third terms.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Instructors: Staff.

PE 37. Beginning Kayaking. *3 units.* 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 proficient swimmers or be able to successfully complete an in-water swim test. Instructors: Staff.

PE 38. Water Polo. *3 units; first 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. Instructor: Staff.

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. Instructor: Staff.

PE 48. T'ai-Chi Ch'uan, Beginning and Intermediate. *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. Instructors: 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. *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 course will review all fundamentals with a refinement of winning shots, serves, and daily games. Instructors: Staff.

PE 56. Squash, Beginning, Intermediate, Advanced. *3 units; first 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 and Intermediate. *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. Interme-diate level focuses on improving technique, footwork, and court positioning, with instruction on approach shots, volleys, overheads, and lobs. Instructors: Staff.

PE 70. Weight Training, Beginning/Intermediate. *3 units; first, second, third terms.* Active participation in a strength and condi-tioning 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. 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 ad-dressing components including muscular strength, foot speed, agil-ity, cardiovascular conditioning and flexibility. Instructor: Staff.

PE 77. Volleyball, Beginning and Intermediate. *3 units; second term.* Fundamental instruction on drills, strategies, and rules, with game-playing opportunities. Basics of serve, pass, set, spike, de-fense, and court position will be taught. Intermediate level focuses on skill development to a more competitive standard and features multiple offenses and understanding officiating. Instructors: Staff.

PE 81. Bouldering. *3 units; first, second, third terms.* Taught at the Caltech bouldering cave, Brown Gym. During this introduc-tory 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, sec-ond, 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 equip-ment, 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 85 ab. Intercollegiate Track and Field Teams. *3 units; second, third terms.* Coach: Raphelson.

PE 87 ab. Intercollegiate Swimming and Diving Teams. *3 units; first, second terms.* Coach: Brabson.

PE 89 ab. Intercollegiate Fencing Teams. *3 units; first, second terms.* Coach: Corbit.

PE 90 abc. Intercollegiate Water Polo Teams. *3 units; first, second, third terms.* Coach: Bonafede.

PE 91 ab. Intercollegiate Basketball Teams. *3 units; first, second terms.* Coaches: Eslinger, Reyes.

PE 92. Intercollegiate Soccer Teams. *3 units; first term.* Coaches: Murray, Gould.

PE 93 ab. Intercollegiate Baseball Team. *3 units; second, third terms.* Coach: Whitehead.

PE 95 ab. Intercollegiate Tennis Teams. *3 units; second, third terms.* Coach: Gamble.

PE 97. Intercollegiate Cross-Country Teams. *3 units; first term.* Coach: Raphelson.

PE 99. Intercollegiate Volleyball Team. *3 units; first term.* Coaches: 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: Cheung, Hsieh, Refael, 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. Instructors: Porter, Cheung, Filippone.

Ph 3. Introductory Physics Laboratory. *6 units (0-3-3); first, second, third terms. Prerequisites: Ph 1 a or instructor's permission.* Introduction to experimental physics and data analysis, with techniques relevant to all fields that deal in quantitative data. Specific physics topics include ion trapping, harmonic motion, mechanical resonance, and precision interferometry. Broader skills covered include introductions to essential electronic equipment used in modern research labs, basic digital data acquisition and analysis, statistical interpretation of quantitative data, professional record keeping and documentation of experimental research, and an introduction to the Mathematica programming language. 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).* For course description, see Freshman Seminar. Not offered 2019–20.

Ph 5. Analog Electronics for Physicists. *9 units (0-5-4); first term. Prerequisites: Ph1abc, Ma1abc, Ma2 taken concurrently.* A fast-paced laboratory course covering the design, construction, and testing of practical analog and interface circuits, with emphasis on applications of operational amplifiers. No prior experience with electronics is required. Basic linear and nonlinear elements and circuits are studied, including amplifiers, filters, oscillators and other signal conditioning circuits. Each week includes a 45 minute lecture/recitation and a 2½ hour laboratory. 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 2 a or Ph 12 a, Ma 2, Ph 3, Ph 2 b or Ph 12 b (may be taken concurrently), Ma 3 (may be taken concurrently).* A laboratory introduction to experimental physics and data analysis. Experiments use research-grade equipment and techniques to investigate topics in classical electrodynamics, resonance phenomena, waves, and other physical phenomena. Students develop critical, quantitative

710

evaluations of the relevant physical theories; they work individually and choose which experiments to conduct. Each week includes a 30-minute individual recitation and a 3 hour laboratory. Instructors: Rice, Politzer.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisites: Ph6, Ph2b or Ph12b, Ph2c or Ph12c taken concurrently.* A laboratory course continuing the study of experimental physics introduced in Physics 6. The course introduces some of the equipment and tech-niques used in quantum, condensed matter, nuclear, and particle physics. The menu of experiments includes some classics which informed the development of the modern quantum theory, including electron diffraction, the Stern-Gerlach experiment, Compton scat-tering, and the Mössbauer Effect. The course format follows that of Physics 6: students work individually and choose which experi-ments to conduct, and each week includes a 30 minute individual recitation and a 3 hour laboratory. 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 ex-plore background material related to seminar topics and to answer questions that arise. The course will also help students find faculty sponsors for individual research projects. Graded pass/fail. Instruc-tor: Spiropulu.

711

FS/Ph 11 abc. Freshman Seminar: Beyond Physics. *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 classi-cal 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, Simmons-Duffin.

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); second, third terms. 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, Weinstein.

Ph 50 ab. Caltech Physics League. *3 units (1-0-2); first, second terms. Prerequisites: Ph 1 abc.* This course serves as a physics club, meeting weekly to discuss and analyze real-world problems in 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. Instructors: Refael, Patterson.

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. Prerequisites: Ph 7 or instructor's permission.* Advanced preparation for laboratory research. Dual emphasis on

practical skills used in modern research groups and historic experiments that illuminate important theoretical concepts. Topics include advanced signal acquisition, conditioning, and data processing, introductions to widely-used optical devices and techniques, laser-frequency stabilization, and classic experiments such as magnetic resonance, optical pumping, and doppler-free spectroscopy. Fundamentals of vacuum engineering, thin-film sample growth, and cryogenics are occasionally offered. Special topics and student-led projects are available on request. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisites: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ken Libbrecht).* Open only to senior physics majors. This research must be supervised by a faculty member, the student's 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.

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 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. Offered in alternate years. Not offered 2019–20.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6).* For course description, see Astrophysics.

713

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph1abc, Ma2, or equivalent.* A laboratory course intended for graduate students, it covers the design, construction, and testing of simple, practical analog and interface circuits useful for signal conditioning and experiment control in the laboratory. No prior experience with electronics is required. Students will use operational amplifiers, analog multipliers, diodes, bipolar transistors, and passive circuit elements. Each week includes a 45 minute lecture/recitation and a 2½ hour laboratory. The course culminates in a two-week project of the student's choosing.

Ph 106 abc. Topics in Classical Physics. *9 units (4-0-5); 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. Ph106a will be devoted to mechanics, including Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, central forces, and rigid-body motion. Ph106b will be devoted to fundamentals of electrostatics, magnetostatics, and electrodynamics, including boundary-value problems, multipole expansions, electromagnetic waves, and radiation. It will also cover special relativity. Ph106c will cover advanced topics in electromagnetism and an introduction to classical optics. Instructors: Weinstein, Golwala, Hutzler.

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 abc. Physics of Measurement. *9 units (3-0-6); first, third 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. Part c not offered in 2019–20. Instructor: Roukes.

CS/Ph 120. Quantum Cryptography. *9 units (3-0-6); first term.* For course description, see Computer Science.

Ph 121 abc. Computational Physics Lab. *6 units (0-6-0); first, second, third terms.* Many of the recent advances in physics are attributed to progress in computational power. In the advanced computational lab, students will hone their computational skills bu working through projects inspired by junior level classes (such as classical mechanics and E, statistical mechanics, quantum mechanics and quantum many-body physics). This course will primarily be in Py-

thon and Mathematica. This course is offered pass/fail. Instructors: Simmons-Duffin, Motrunich.

Ph 125 abc. Quantum Mechanics. *9 units (4-0-5); 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. Instructor: Wise.

Ph 127 abc. Statistical Physics. *9 units (4-0-5); 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. Instructors: Motrunich, Brandao.

Ph 129 abc. Mathematical Methods of Physics. *9 units (4-0-5); 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 covers probability and statistics in physics. Second term focuses on group theoretic methods in physics. Third term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. The three terms can be taken independently. Instructors: Porter, Chen, Oguri.

Ph 135. Introduction to Condensed Matter. *9 units (3-0-6); first term. Prerequisites: Ph 125 abc or equivalent or instructor's permission.* This course is an 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. Instructor: Refael.

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 ther-

modynamics, 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. Offered in alternate years. Not offered 2019–20.

Ph/APh 137 abc. Atoms and Photons. *9 units (3-0-6); first, second terms. Prerequisites: Ph 125 abc or equivalent, or instructor's permission.* This course will provide an introduction to the interaction of atomic systems with photons. The main emphasis is on laying the foundation for understanding current research that utilizes cold atoms and molecules as well as quantized light fields. First term: resonance phenomena, atomic/molecular structure, and the semiclassical interaction of atoms/molecules with static and oscillating electromagnetic fields. Techniques such as laser cooling/trapping, coherent manipulation and control of atomic systems. Second term: quantization of light fields, quantized light matter interaction, open system dynamics, entanglement, master equations, quantum jump formalism. Applications to cavity QED, optical lattices, and Rydberg arrays. Third term [not offered 19-20]: Topics in contemporary research. Possible areas include introduction to ultracold atoms, atomic clocks, searches for fundamental symmetry violations, synthetic quantum matter, and solid state quantum optics platforms. The emphasis will be on reading primary and contemporary literature to understand ongoing experiments. Instructors: Hutzler, Endres.

APh/Ph 138 ab. Quantum Hardware and Techniques. *9 units (3-0-6).* For course description, see Applied Physics.

Ph 139. Introduction to High Energy Physics. *9 units (3-0-6); third term. Prerequisites: Ph 125 abc or equivalent, or instructor's permission.* This course provides an 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. Instructor: Patterson.

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 Physics. *Units in accordance with work accomplished.* Undergraduate students registering for 6 or more units

of Ph 172 must provide a brief written summary of their work, not to exceed 3 pages, to the option rep at the end of the term. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

Ph 177. Advanced Experimental Physics. *9 units (0-4-5); second, third terms. Prerequisites: Ph 7, Ph 106 a, Ph 125 a or equivalents.* A one-term laboratory course which will require students to design, assemble, calibrate, and use an apparatus to conduct a nontrivial experiment involving quantum optics or other current research area of physics. Students will work as part of a small team to reproduce the results of a published research paper. Each team will be guided by an instructor who will meet weekly with the students; the students are each expected to spend an average of 4 hours/week in the laboratory and the remainder for study and design. Enrollment is limited. Permission of the instructors required. Instructors: Rice, Hutzler.

CNS/Bi/Ph/CS/NB 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph 198. Special Topics in Physics. *Units in accordance with work accomplished.* Topics will vary year to year and may include hands-on laboratory work, team projects and a survey of modern physics research. Instructor: Staff.

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 2019–20.

717

Ph 201. Candidacy Physics Fitness. *9 units (3-0-6); third term.* The course will review problem solving techniques and physics applications from the undergraduate physics college curriculum. In particular, we will touch on the main topics covered in the written candidacy exam: classical mechanics, electromagnetism, statistical mechanics and quantum physics, optics, basic mathematical methods of physics, and the physical origin of everyday phenomena. Instructor: Endres.

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, Kapustin.

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. Not offered 2019–20.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second terms. Prerequisites: Ph 125 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. Part c not offered in 2019–20. Instructors: Preskill, Brandao.

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, Kitaev.

Ph 229 ab. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first term. Prerequisites: Ph 205 abc or equivalent.* A course on conformal field theory and the conformal bootstrap. Students should have some background in quantum field theory. Topics will include the renormalization group, phase transitions, universality, scale vs. conformal invariance, conformal symmetry, operator product expansion, state-operator correspondence, conformal blocks,

the bootstrap equations, bootstrap in d=2 dimensions, numerical bootstrap methods in d>2, analytical bootstrap methods, introduction to AdS/CFT. Possible additional topics (time permitting) include superconformal field theories, entanglement entropy, monotonicity theorems, and conformal perturbation theory. Instructor: Kapustin.

Ph 230 ab. Elementary Particle Theory. *9 units (3-0-6); first term. 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: Zurek. Only offered in fall quarter in the 2019-20 academic year

Ph 236 abc. General 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. Offered in alternate years. Part c not offered in 2019–20. Instructors: Chen, Teukolsky.

Ph 237. Gravitational Radiation. *9 units (3-0-6); third term. Prerequisites: Ph 106 bc, Ph 12 b or equivalents.* Special topics in Gravitational-wave Detection. Physics of interferometers, limits of measurement, coherent quantum feedback, noise, data analysis. Instructor: Adhikari.

Ph 242 ab. Physics Seminar. *4 units (2-0-2); first, second terms.* An introduction to independent research, including training in relevant professional skills and discussion of current Caltech research areas with Caltech faculty, postdocs, and students. One meeting per week plus student projects. Registration restricted to first-year graduate students in physics. Instructor: Patterson.

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 2019–20.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 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 20. Political-Economic Development and Material Culture. *9 units (3-0-6); second term.* During the 19th-century the American economy, despite the Civil War, caught up to and surpassed all European economies. How did the likes of Singer, John Deere and Seth Thomas -- latecomers to the markets they served—come to dominate those markets both domestically and internationally? Why did the technology of interchangeable parts and mass production become known as 'the American system' when much of that technology was imported from Europe? What role did government play in facilitating or thwarting innovation and economic growth? This course will explore such questions as reflected in the ordinary things people collect under the label 'antiques'. What do we learn from the fact that we can document a half dozen American manufacturers of apple peelers but not a single comparable European company? Why is the hand sewn quilt a nearly unique American folk art form and what does the evolution of quilting patterns tell us about technology and economic prosperity? What do baking powder cans as a category of collectible tell us about the politics of federal versus state regulation? Students will be expected to each choose a topic that asks such questions and to explore possible answers, all with an eye to understanding the interplay of economics, politics, and demography. Instructor: Ordeshook.

BEM/Ec/PS 80. Frontiers in Social Sciences. *1 unit (1-0-0).* For course description, see Business, Economics, and Management.

PS 97. Undergraduate Research. *Unites to be arranged; any term. Prerequisites: advanced political science and instructor's permission.* This course offers 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); first, second terms. 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); first 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. Not offered 2019–20.

PS 122. Political Representation. *9 units (3-0-6); third term. Prerequisites: PS 12.* Why does the U.S. Constitution feature separation of powers and protect states' rights? Should the Senate have a filibuster? When can Congress agree on the best policy for the country (and what does "best" even mean)? This course uses a rigorous set of tools including game theory and social choice to help students understand the effectiveness of American democracy to represent diverse interests. Using the tools, we study U.S. electoral systems, Congress, federalism, and the courts, with a focus on understanding how the country has tried to overcome the challenges of group decision making and the inevitable conflicts that arise between the branches of government and divided political interests. Students will leave the course with a deeper understanding of how rules and strategy shape U.S. democracy. Not offered 2019–20.

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 125. Analyzing Political Conflict and Violence. *9 units (3-0-6); second term.* This course examines the causes of and solutions for conflict and violence: Why do wars occur and how do we stop them? We cover topics such as terrorism, ethnic violence, civil wars, the Israeli-Palestinian conflict, repression, revolutions, and inter-state wars. We study these phenomena using the rational choice framework and modern tools in data analysis. The goals of the class are to explain conflicts and their terminations as outcomes of strategic decision-making and to understand the empirical strengths and weakness of current explanations. Instructor: Gibilisco.

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 2019–20.

722

PS 132. Formal Theories in Political Science. *9 units (3-0-6); first term. Prerequisites: PS 12 and Ec/PS 172.* 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); first 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. Not offered 2019–20.

PS/SS 139. Comparative Politics. *9 units (3-0-6); third term. Prerequisites: PS 12.* This course offers a broad introduction to the theoretical and empirical research in comparative political economy. An emphasis will be placed on the parallel process of political and economic development and its consequences on current democratic political institutions such as: electoral rules, party systems, parliamentary versus presidential governments, legislatures, judicial systems, and bureaucratic agencies as exemplified in central bank politics. We will study the differential impact of these political institutions on the type of policies they implement and the economic outcomes they produce. The main objective of the course will be to assess the robustness of the analyzed theories in light of their empirical support, coming mainly from statistical analysis. Instructor: Lopez-Moctezuma.

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. Instructor: 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 13. Introduction to Cognitive Neuroscience. *9 units (3-0-6); third term.* This course will provide an introduction to what we know

about the fascinating link between the brain, the mind, and behavior. We will start with a basic review of the brain as a biological organ, its evolution, development, and its basic operations including visual and others senses. Next, we will discuss how the brain gives rise to a wide variety of complex behaviors, memory, social and emotional behaviors. The course will finally introduce students to the wider neurophilosophical questions concerning freewill, death and morality. Instructor: Mobbs.

Psy 25. Reading and Research in Psychology. *Units determined by the instructor.* Not available for credit toward humanities–social science requirement. Written report required. Graded pass/fail. Not offered 2019–20.

Psy 90. Applied Neuropsychology of Learning. *9 units (3-0-6); first term.* An introduction to the neuropsychological mechanisms associated with learning and creativity, and to how different factors and behaviors impede and enhance them. No previous coursework in psychology or neuroscience is required. The course includes labs in which the students will test various hypothesis about their own learning processes. Graded or P/F. Note that this course can be used to fulfill the overall HSS core requirements, but does not count towards the introductory or advanced social science requirement. Offered alternating years. Not offered 2019–20.

Psy 101. Selected Topics in Psychology. *Units determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

CNS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6); second, third terms.* For course description, see Computation and Neural Systems.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5); second 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 inter-temporal 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. Instructor: O'Doherty.

Ec/Psy 109 ab. Frontiers in Behavioral Economics. *9 units (3-0-6).* For course description, see Economics.

Psy 115. Social Psychology. *9 units (3-0-6); first term.* The study of how people think about other people and behave toward or around others. Topics include social cognition and emotions (theory of mind and empathy), their development from childhood to old age, impairments in social functions, altruism and cooperation, social groups (ingroup and outgroup), attribution and stereotypes. The class also presents evidence on how these social phenomena are implemented in the human brain and introduces behavioral and neuroscientific methods used in social psychology and social neuroscience. Instructor: Dubois.

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 2019–20.

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 2019–20.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Psy/CNS 132. Computational Reinforcement-learning in Biological and Non-biological Systems. *9 units (3-0-6); third term.* Reinforcement-learning concerns the computational principles by which animals and artificial agents can learn to select actions in their environment in order to maximize their future rewards. Over the past 50 years there has been a rich interplay between the development and application of reinforcement-learning models in artificial intelligence, and the investigation of reinforcement-learning in biological systems, including humans. This course will review this rich literature, covering the psychology of animal-learning, the neurobiology of reward and reinforcement, and the theoretical basis and application of reinforcement-learning models to biological and non-biological systems. Instructor: O'Doherty.

Psy 133. Computation, Cognition and Consciousness. *9 units (3-0-6); second term.* This course will critically examine the impact of recent advances in computational neuroscience for central prob-

lems of philosophy of mind. Beginning with a historical overview of computationalism (the thesis that mental states are computational states), the course will examine how psychological explanation may be understood in computational terms across a variety of levels of description, from sub-neuronal and single neuroncomputation to circuit and network levels. Specific issues will include: whether computation provides unifying psychological principles across species; whether specific mental states such as pain are computational states; digital/analog computation, dynamical systems, and mental representation; whether conscious experience can be understood as a computational process. Not offered 2019–20.

Bi/CNS/NB/Psy 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

Pl/CNS/NB/Bi/Psy 161. Consciousness. *9 units (3-0-6).* For course description, see Philosophy.

CNS/Bi/Psy/NB 176. Cognition. *9 units (4-0-5); third term.* For course description, see Computation and Neural Systems.

Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6); third term. Prerequisites: Bi/CNS/NB/Psy 150 or instructor's permission.* Emotions are at the forefront of most human endeavors. Emotions aid us in decision-making (gut feelings), help us remember, torment us, yet have ultimately helped us to survive. Over the past few decades, we have begun to characterize the neural systems that extend from primitive affective response such as fight or flight to the complex emotions experienced by humans including guilt, envy, empathy and social pain. This course will begin with an in-depth examination of the neurobiological systems that underlie negative and positive emotions and move onto weekly discussions, based on assigned journal articles that highlight both rudimentary and complex emotions. The final weeks will be devoted to exploring how the neurobiological systems are disrupted in affective disorders including anxiety, aggression and psychopathy. In addition to these discussions and readings, each student will be required to write a review paper or produce a short movie on a topic related to one of the emotions discussed in these seminars and its underlying neural mechanisms. Instructor: Mobbs.

Psy 283 abc. Graduate Proseminar in Social and Decision Neuroscience. *3 units (1.5-0-1.5); first, second, and third terms.* The course involves student presentations of their research, reading and discussion of recent research in social and decision neuroscience, and development of professional skill such as scientific writing and speaking, research ethics, writing grants and peer review. This course is only open to graduate students in the Social and Decision

Neuroscience, Computational and Neural Systems and Social Science PhD programs. Instructors: Camerer, Rangel, Camerer.

Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0); second term.* Select faculty will present their research background, methods, and a sampling of current questions/studies. Background readings and pdf of presentation will be provided. Not offered 2019–20.

SCIENTIFIC AND ENGINEERING COMMUNICATION

SEC 10. Technical Seminar Presentations. *3 units (3-0-0); first, second, third terms; (Seniors required to take this course are given priority in registration.).* The purpose of this course is to equip students with the skills, knowledge, and experience necessary to give effective oral presentations. The course will include a mix of formal instruction, group discussions, practice presentations, and individual feedback. Limited enrollment. May not be repeated for credit. Instructor: Javier.

SEC 11. Written Academic Communication in Engineering and Applied Science. *3 units (1-0-2); terms to be arranged.* This class provides the opportunity for students to gain experience in academic 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 an academic genre on that topic. Appropriate genres include the engineering report, review paper, or a peer-reviewed journal paper. Students will receive instruction in academic discourse in engineering and applied sciences as well as substantial feedback on their work-in-progress. This course is recommended for students who plan to attend graduate school or who wish to work toward a senior thesis or academic publication. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 12. Written Professional Communication in Engineering and Applied Sciences. *3 units (1-0-2); Terms to be arranged. Prerequisites: None.* This class introduces students to common workplace genres of writing in professional (non-academic) fields in engineering and the applied sciences. Students will compose professional technical writing in multiple genres and consider the varied audiences and goals of writing in various engineering and applied sciences industries. Genres covered may include specifications; proposals; progress reports; recommendation reports; code

documentation; contracts, patents, and trademarks; user manuals or instructions; formal memos; business emails; or instant message communication. This course is recommended for students who plan to seek jobs in industry. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 13. Written Communication about Engineering and Applied Sciences to Non-Experts. *3 units (1-0-2); Terms to be arranged. Prerequisites: None.* Engineers and applied scientists often work on highly technical, specialized projects. However, their work often is of interest to readers with varied levels of area and technical expertise-including investors, community stakeholders, government regulators, consumers, voters, students, and enthusiasts. This course introduces students to diverse types of writing about technical engineering and applied science topics intended for these "non-expert" readers who lack some or all of the technical knowledge the author has. Students will compose multiple texts written for different purposes and to different types of non-expert readers. This course is recommended for students who may plan entrepreneurial, non-profit, or government careers, where communication to non-experts is crucial to success. It may also interest students who enjoy public advocacy or creative writing about technical topics. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 100. Special Topics in Scientific and Engineering Communication. *Units to be arranged; terms to be arranged in consultation with the instructor.* Content may vary from year to year, at a level suitable for advanced undergraduate or graduate students. Topics will be chosen to meet the emerging needs of students. Instructor: Javier.

E/SEC 102. Scientific and Technology Entrepreneurship. *9 units (3-0-6).* For course description, see Engineering.

E/SEC 103. Management of Technology. *9 units (3-0-6).* For course description, see Engineering.

SEC 111. Effective Communication Strategies for Engineers and Scientists. *6 units (3-0-3); third term. Prerequisites: none.* This graduate course offers instruction and practice in written and oral communication for scientists and engineers. The course is designed to increase students' effectiveness in communicating complex technical information to diverse audiences and to deepen their understanding of communication tools and techniques. Students will explore scientific storytelling through multiple communication genres, including research manuscripts and presentations, visual

narratives, and traditional and social media channels. In-class work-shops will provide students with the opportunity to revise their work and consider feedback from instructors and peers. (Registration by application only, and EAS graduate students are given priority.) Instructor: Javier.

SEC 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, brain-storming 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 out-lined 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 compe-tent in acquiring and processing data. Instructor: to be determined.

SEC 130. Science Activation: Bringing Science to Society. *6 units (3-0-3); second term. Prerequisites: none.* Working with policy makers is more than science communication. It requires a bilat-eral approach to exploring complex problems and solutions that encompass societal objectives as well as physical requirements. An intellectual understanding of the differences communication norms in the research and policy realms can help scientists make better decisions about how to communicate about their work and engage with policy makers to get it used. This course combines analysis of the differences in communication norms with practical experience in communicating and developing relationships with elected officials and their staffs. Instructor: Lucy Jones and John Bwarie.

SOCIAL SCIENCE

SS 101. Selected Topics in Social Science. *Units to be deter-mined by arrangement with the instructor; offered by announce-ment.* Not available for social science credit unless specifically ap-proved by social science faculty. Instructors: Staff, visiting lecturers.

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).* For course description, see Economics.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6).* 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).* For course description, see Economics.

PS/SS 139. Comparative Politics. *9 units (3-0-6).* For course description, see Political Science.

CS/SS/Ec 149. Algorithmic Economics. *9 units (3-0-6).* For course description, see Computer Science.

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: Tamuz, Saito, Pomatto.

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, Lopez-Moctezuma.

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: Doval, Echenique, Palfrey.

SS 209. Behavioral Economics. *9 units (3-0-6); first 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. Instructor: Camerer.

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. Instructors: Gibilisco, Agranov.

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: Doval, Echenique/Pomatto, Saito.

SS 213 abc. Financial Economics. *9 units (3-2-4); First, second, third terms.* Mathematical finance: Pricing financial derivatives, risk management, and optimal portfolio selection. Methods of stochastic, Ito calculus for models driven by Brownian motion. Asset pricing theory: Mean-variance theory, information economics, continuous-time finance and differential equations, intertemporal consumption-based asset pricing theories, recent developments in intermediary-based and behavioral asset pricing theories. Behavioral finance: Empirical facts about asset prices, investor trading behavior, and firm behavior. Psychology about investor preferences and beliefs. Behavioral finance models that explain empirical facts. Trading strategies implemented by hedge funds. Prescriptive behavioral finance that aims at helping individuals and institutions to make better financial decisions. Instructors: Jin.

SS 218. Neuroscience Applications to Economics and Politics. *9 units (3-0-6); second term.* Topics in behavioral, affective, and social neuroscience that inform how individuals make economic

decisions. Applications of neuroscience ideas and methods to understanding choice under risk and uncertainty, temporal discounting and self-control, advertisement and preference formation, habit, addiction, and judgment bias. Not offered 2019–20.

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. Instructors: Shum, Xin, Sherman.

SS 223 abc. Topics in Theoretical and Applied Econometrics. *9 units (3-0-6); first, second, third terms. Prerequisites: SS 222 abc; may be repeated for credit.* The courses in this sequence cover advanced methods and tools in econometrics, as well as their applications to a variety of topics in economics, including industrial organization, dynamic choice, information economics, political economy, market design, and behavioural economics. Instructors: Shum, Sherman, Xin.

SS 224. Social Science Data. *9 units (3-3-3); first term.* This course provides broad coverage of empirical methods in the social sciences. This includes both methods of data collection and practical aspects of data analysis, as well as related issues of survey design, experimental design, techniques for handling large datasets, and issues specific to the collection and analysis of field and historical data. This course also provides students with hands-on experience with data. Open to Social Science graduate students only. Instructor: Alvarez.

SS 225. Experimetrics. *9 units (3-0-6); third 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. Not offered 2019–20.

SS 228 abc. Applied Empirical Methods in the Social Sciences. *9 units (3-0-6); first, second, third terms.* Course covers methods used in contemporary applied empirical work in a variety of social sciences. Topics covered include (a) maximum likelihood, Bayesian estimation, management and computation of large datasets, (b) reduced form methods like instrumental variables (IV), difference-in-differences (DID), natural experiments, event study and panel data methods, and (c) structural estimation. Emphasis is on the application of tools to substantive social science problems rather than sta-

tistical theory, in areas including political science, political economy, corporate finance, and accounting. Application focus will vary with instructor interests. Instructors: Katz, Ewens, Lopez-Moctezuma.

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: Hoffman, Rosenthal.

SS 231 abc. American and Comparative Politics. *9 units (3-0-6); first, second, third terms. Prerequisites: SS 202 abc, or permission of the instructor.* An advanced graduate Social Science sequence in American and comparative politics. The sequence will focus on political institutions and behavior, introducing students to the important theories of American and comparative politics. Students will learn how historical, observational, and experimental data are used in American and comparative political analysis. Instructors: Alvarez, Staff.

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 2019–20.

SS 282 abc. Graduate Proseminar in Social Science. *3 units (1.5-0-1.5); 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. Instructors: Gibilisco, Doval.

SS 299. Writing. *6 units (3-0-3); summer term.* This course is designed for students to improve their ability for written expression in the English language. This course is only open to graduate students

in the Social Decision Neuroscience and Social Science Ph.D. programs. Instructor: Staff.

SS 300. Research in Social Science. *Units to be arranged.*

STUDENT ACTIVITIES

SA 15 abc. Student Publications. *SA 15a 5 units (2-0-3), first term; SA 15bc 4 units (1-0-3), second and third terms. Prerequisites: SA 15a is a prerequisite for SA 15b and SA 15c.* This course will enable students to produce quality, journalistically-crafted stories for the Tech newspaper. It will teach journalistic values of clarity, accuracy, fairness and balance, and acquaint the students with the primary elements of journalism, including reporting, basic story structure and news/opinion-writing distinctions. Students will produce feature stories for the Tech (with assigned art or graphics) about campus life and activities, profiles of campus faculty or staff, and issues of campus community interest. May be re-taken for credit. Instructor: Kipling.

SA 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.

SA 42. Computer Science Education in K-14 Settings Practicum. *4 units (0-2-2); first, second, third terms. Prerequisites: CS 42.* This course is a follow-on for students who have already taken CS 42 and would like to continue as part of a teaching group partnered with a local school or community college. Each week students are expected to spend about 2 hours teaching and 2 hours developing curricula. Students may take SA 42 multiple times. Graded pass/fail only. Not offered first term 2019–20. Instructor: Ralph.

SA 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 www.deans.caltech.edu/Services/student_taught_courses.

SA 80 abc. Health Advocates. *3 units (1-1-1); first, second, third terms.* A course designed to involve students with health care and education, develop familiarity with common college health prob-

lems, 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.

SA 81 ab. Peer Advocates. *3 units (1-1-1); first and third terms.* A course designed to involve students with appropriate peer support and education, develop familiarity with common college mental health problems, and provide peer mental health support to students on and off campus. Peer Advocates will begin the course in the spring term prior to the year of service, and continue coursework in the following fall term. Spring term: Active listening skills, identifying students in distress, suicide prevention training using the QPR (Question, Persuade, Refer) model; Fall term: Lectures and discussions on substance abuse, dating violence, sexual assault, depression, and other relevant mental health topics, as well as ongoing consultation about practical experience. Enrolled with permission only. Instructor: Staff.

VISUAL CULTURE

Hum/VC 49. Consuming Victorian Media. *9 units (3-0-6).* For course description, see Humanities.

Hum/VC 50. Introduction to Film. *9 units (3-0-6); third term.* For course description, see Humanities.

VC 60. Art/Media. *Units to be determined by the instructor; offered by announcement.* A practice-based course taught by a visiting artist in residence. See registrar's announcement for details. Instructor: TBD.

VC 70. Traditions of Japanese Art. *9 units (3-0-6); third 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 2019–20.

VC 72. Data, Algorithms and Society. *9 units (3-0-6); third term.* For course description, see CS/IDS 162. Taught concurrently

with CS/IDS 162 and can only be taken once as VC 72 or CS/IDS 162. Instructors: Mushkin, Ralph.

E/VC 88. Critical Making. *9 units (3-0-6).* For course description, see Engineering.

E/H/VC 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6).* For course description, see Engineering.

VC 104. French Cinema. *9 units (3-0-6).* For course description, see L 104. Not offered 2019–20. Instructor: Orcel.

En/VC 108. Volcanoes. *9 units (3-0-6).* For class description, see English.

L/VC 109. Introduction to French Cinema from Its Beginning to the Present. *9 units (3-0-6).* For class description, see Languages.

En/VC 117. Picturing the Universe. *9 units (3-0-6).* For class description, see English.

L/VC 153. Refugees and Migrants' Visual and Textual Representations. *9 units (3-0-6).* For course description, see Languages.

En/VC 160 ab. Classical Hollywood Cinema. *9 units (3-0-6).* For course description, see English.

En/VC 161. The New Hollywood. *9 units (3-0-6).* For course description, see English.

VC 169. The Arts of Dynastic China. *9 units (3-0-6); third 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.

VC 170. Special Topics in Visual Culture. *9 units (3-0-6); offered by announcement.* An advanced humanities course on a special topic in visual culture. Topics may include art history, film, digital and print media, architecture, photography or cartography. It is usually taught by new or visiting faculty. The course may be re-taken for credit except as noted in the course announcement. Limited to 15 students. See registrar's announcement for details. Instructor: Staff.

VC 171. 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. Not offered 2019–20.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. *9 units (3-0-6).* For course description, see History.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. *9 units (3-0-6).* For course description, see History.

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, Sarmiento.

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 posi-

tion, 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. Instructor: Daley.

Wr 3. Reading and Composing Academic Writing. *9 units (1-0-8); 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. Instructor: Daley.

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. Instructor: Hall.

Wr 50. Tutorial in Writing. *1-3 units to be arranged; first, second, third terms.* 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. Instructor: Hall.

En/Wr 84. Writing About Science. *9 units (3-0-6); third term.* For course description, see English.

ESL/Wr 107. Graduate Writing Seminar. *6 units (3-0-3).* For course description, see English as a Second Language.

ESL/Wr 108. Intermedia Graduate Writing Seminar. *6 units (3-0-3).* For course description, see English as a Second Language.

Trustees, Administration, Faculty

Trustees, Administration, Faculty

741

743

Trustees, Administration, Faculty

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)—R. A. Andersen, Chair; M. Meister, Vice Chair; J. Brackman, J. Campbell (alternate), J. Gumer (alternate), L. C. Hsieh-Wilson, K. C. Lencioni*, C. Lois (alternate), D. J. Mayo*, L. E. Quenee* J. Scapa*, C. W. Scislowicz* (alternate), R. P. Seligman* (alternate), P. Vaishampayan, Advisor: Jennifer T. Lum (or her designee)

Benefits (Reports to the Vice President of Administration and Chief Financial Officer)—P. T. Hoffman, Chair; A. Boladian, K. Bradshaw*, B. Clemons, R. Fadet, C. Hart*, M. Jaross*, A. Leonard, L. Livesay, J. M. McCallin*, L. Moffit*, S. E. Patterson*, R. M. Roessler*, A. I. Sargent, S. Scoville

Biosafety [fills the role of Caltech's Institutional Biosafety Committee—IBC] (Reports to the Provost)—J. D. Leadbetter, Chair; A. Aravin, S. Chatterjee, C. Cortese, G. Fisher-Adams*, F. Hanner, R. Ismagilov, K. Lencioni*, D. J. Mayo (alternate), L. Quenee*, J. Scapa* (alternate), C. Scislowicz*, R. Seligman*, P. Vaishampayan, Advisor: Jennifer T. Lum (or her designee)

Committee on Classified Research and Publication Restrictions at JPL (Reports to the President)—D. I. Meiron, Chair; D. Gallagher, R. Murray, T. A. Prince, M. Simons, P. O. Wennberg, J. Zmuidzinas

Computing Advisory Committee (Reports to the Provost and the Vice President of Administration and Chief Financial Officer)—M. Spiropulu, Chair; K. Bhattacharya*, G. K. Chan, J. Chang*, T. Colonius, M. Hari‡, G. J. Jensen, V. R. Lambert†, M. Mayalu§ ,S. E. Patterson*, M. S. Shum, A. F. Thompson, J. Zhang

Committee on Undergraduate Education (Reports to the Provost)—C. A. Weinstein*, Chair; W. Brown*, K. M. Gilmartin*, A. Gupta*, B. Hay, C. Horii, C. Jurca, J. Leadbetter*, A. Lopez, M. Okumura, C. Parker, G. Refael, C. Salinas*, E. Salzman, J. E. Shepherd*, M. Spiropulu, A. J. Weinstein*

Environmental Health and Safety (Reports to the President)—D. A. Tirrell, Chair; K. Bhattacharya, J. W. Cowell*, P. D. Koyzis*, C. Scislowicz*, J. E. Shepherd, M. Steurbaut

Institute Academic Council (IACC)— David A. Tirrell, Chair; D. A. Dougherty, J. P. Grotzinger, F. Harrison, S. L. Mayo, G. Ravichandran, T. F. Rosenbaum, J-L Rosenthal

Institute Administrative Council (IAC)—T. F. Rosenbaum, Chair; D. Bailey, K. Bhattacharya, S. Chabner, J. Chang, J. W. Cowell, D. Dougherty, F. Farina, K. M. Gilmartin, J. P. Grotzinger, K. Hargreaves, F. A. Harrison, L. James, D. Jergovic, P. D. Koyzis, J. Lum, L. Malcom-Piqueux, S. L. Mayo, J. M. McCallin, V. A. Otten, S. E. Patterson, G. Ravichandran, D. C. Rees, S. H. Richland, J-L Rosenthal, R. P. Seligman, J. E. Shepherd, M. Spiropulu, M. Steurbaut, D. A. Tirrell, M. M. Watkins, M. L. Webster, C. A. Weinstein

Institute Art (Reports to the President)—T. Schneider, Chair, J-P Avouac, J. Buchwald, P. Collopy*, T. Davis*, M. Elowitz, K. T. Faber, K. Hargreaves*, D. Kremers, M. Lewis, Z. Mo, P. Perona

President's Diversity Council (Reports to the President through the Provost)—C. Weinstein*, Chair; W. M. Clemons, Jr., A. Emami, F. Harrison, V. J. Orphan, R. Ravichandran, B. Stolz, N. Wey-Gomez, B. Wold

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. A. Andersen, Vice Chair, J. Ensminger, M. Ewens, M. J. Gibson, I. Hildebrandt, L. Lettieri, P. Perona, L. Quenee*, K. Reimer, C. W. Scislowicz*, R. P. Seligman*, J. M. Tyszka*, P. Vaishampayan, Advisor: Jennifer T. Lum (or her designee); Observer: G. Fisher-Adams

Radiation Safety (Reports to the Vice President of Administration and Chief Financial Officer)—D. S. Burnett, Chair; B. W. Filippone, Vice Chair: H. Issaian*, W. L. Johnson, A. Kumagai, C. Scislowicz*, S. Shan

SURF (Reports to the Provost)—R. Murray, Chair, G. Blake, M. Bronner, D. Crewell*, K. M. Gilmartin*, M. Gonzalez*,

E. Mantovan, A. Ponce, M. B. Robbins*,
C. Rypisi*, B. Stolz, T. Tisch*

* ex officio member
† representing graduate students
‡ representing undergraduate students
§ representing postdoctoral scholars

FACULTY OFFICERS AND COMMITTEES 2018–19

Officers
Chair: M. Spiropulu, 2020
Vice Chair: G. A. Blake, 2020
Secretary: R. M. Murray, 2021

Faculty Board
H. A. Atwater, 2022
J. M. Austin, 2020
K. Batygin, 2022
S. Bordoni, 2020
G. K. Chan, 2020
T. K. Dennison, 2021
M. H. Dickinson, 2021
M. Effros, 2022
C. Jurca, 2020
J. N. Katz, 2020
H. A. Knutson, 2020
J. A. Kornfield, 2021
M. Meister, 2022
F. C. Porter, 2022
D. Ramakrishnan, 2020
G. R. Rossman, 2022
E. Rothenberg, 2021
B. M. Stoltz, 2021
A. Wierman, 2021

Ex Officio:
D. A. Dougherty
K. M. Gilmartin
J. P. Grotzinger
F. A. Harrison
S. L. Mayo
G. Ravichandran
D. C. Rees
T. F. Rosenbaum
J-L. Rosenthal
J. E. Shepherd
D. A. Tirrell

Steering
M. Spiropulu, Chair, 2020
G. A. Blake, Vice Chair, 2020
R. M. Murray, Secretary, 2021
K. Bhattacharya*
T. K. Dennison, 2020
G. R. Rossman 2020
E. Rothenberg, 2020

ex officio member

Trustees, Administration, Faculty

B. M. Stoltz, 2020
D. A. Tirrell*
C. A. Weinstein*
A. Wierman, 2020

Academic Freedom and Tenure
C. Jurca, Chair, 2020
J. M. Stock, Vice Chair, 2020
H. A. Lester, 2021
E. Mantovan, 2020
B. J. McKeon, 2021
A. J. Minnich, 2020

Academic Policies
C. S. Parker, Chair, 2021
M. Agranov, 2021
B. Hassibi, 2021
E. Meyerowitz, 2020
A. L. Sessions, 2020

Athletics and Physical Education
T. K. Dennison, Chair, 2022
M. E. Brown, 2022
N. Chun*
J. C. Doyle, 2020
B. W. Filippone, 2020
T. F. Miller, 2021
B. Mitchell*
D. Y. Tsao, 2021

Convocations
W. C. Brown, Chair, 2020
K. M. Gilmartin*
L. C. Hsieh-Wilson, 2021
D. C. Rees*
N-C. Yeh, 2020

Core Curriculum Steering
M. Okumura, Chair, 2021
F. M. Echenique, 2020
M. Flach, 2020
K. M. Gilmartin*
M. L. Hunt, 2021
N. R. Hutzler, 2021
C. Jurca, 2020
C. Salinas*
A. Wierman, 2021
K. G. Zinn, 2022

Curriculum
A. J. Weinstein, Chair, 2022
T. Agapie, 2021
K. M. Gilmartin*
D. I. Meiron, 2020
L. S. Pachter, 2020
E. M. Rains, 2022
C. Salinas*
A. F. Thompson, 2022

Committee on Exchange Programs and Study Abroad (CEPSA)
H. B. Newman, Chair, 2021
J. F. Adkins, 2021

T. Agapie, 2021
C. Daraio, 2020
M. Desbrun, 2022
M. D. Dykstra, 2021
I. Peter, 2020
S. R. Quartz, 2022
C. Salinas*
L. B. Stolper*

Foreign Students and Scholars
A. Hoelz, Chair, 2021
Y. Abu-Mostafa, 2021
C. Daraio, 2021
C. Frankenberg, 2022
A. Rangel, 2020
A. G. Siapas, 2020
I. Smith*

Freshman Admissions
J. R. Leadbetter, Chair, 2022
C. F. Camerer, 2022
D. C. Chan, 2020
N. Chun*
G. A. George, 2022
L. Hillenbrand, 2022
N. H. Katz, 2020
J. Kirschvink, 2022
J. A. Kornfield, 2021
K. G. Libbrecht, 2020
S. Shimojo, 2020
P. P. Vaidyanathan, 2021
D. P. Weitekamp, 2021

Graduate Studies
B. Fultz*, Chair
A. D. Ames*
R. W. Clayton*
W. M. Clemons*
A. Faraon*
K. P. Giapis*
N. Gilmore (non-voting)
V. Gradinaru*
B. A. Hay*
L. Hillenbrand*
N. Lapusta*
D. I. Meiron*
M. Meister*
Y. Ni*
T. R. Palfrey*
R. B. Patterson*
A. Rangel*
D. C. Rees*
P. Schroeder*
A. G. Siapas*
B. M. Stoltz*
A. F. Thompson*
T. G. Vidick*
L. Wang*
E. Winfree*
C. Yang*
Y. Yue*

Health
H. A. Lester, Chair, 2022

ex officio member

J. L. Beauchamp, 2022
F. Eberhardt, 2020
K. M. Gilmartin*
S. Golwala, 2021
J. L. Howes*
A. P. Ingersoll, 2022
J. M. McCallin*
B. Mitchell*
D. C. Rees*
J. Y. Tsai*

Institute Programs
J. R. Greer, Chair, 2020
B. Brophy*
J. M Eiler, 2022
L. C. Hsieh-Wilson, 2022
D. Jergovic*
A. J. Minnich, 2021
L. S. Pachter, 2002

Library
N. Wey-Gomez, Chair, 2022
C. E. Bucholz, 2022
W. A. Goddard, 2022
A. J. Minnich, 2020
H. B. Newman, 2021
L. S. Pachter, 2020

Membership and Bylaws
G. A. Blake, Chair, 2020
K. C. Border, 2022
D. C. Chan, 2022
M. Effros, 2021
R. C. Flagan, 2022
R. M. Murray*
B. P. Wernicke, 2021

Nominating
H. A. Knutson, Chair, 2020
J. F. Alicea, 2020
M. L. Hunt, 2021
C. Jurca, 2020
T. F. Miller, 2020
R. M. Murray*
P. W. Sternberg, 2021

Patents and Relations with Industry
M. L. Roukes, Chair, 2021
R. F. Ismagilov, 2021
S. Mazmanian, 2020
N. A. Pierce, 2020
B. M. Stoltz, 2022
K. J. Vahala, 2020
C. Yang, 2022

Scholarships and Financial Aid
F. Eberhardt, Chair, 2021
G. Blanquart, 2020
N. Chun*
D. Crewell*
K. M. Gilmartin*
J. R. Leadbetter*
C. S. Parker, 2021

STAFF OF INSTRUCTION AND RESEARCH

DIVISION OF BIOLOGY AND BIOLOGICAL ENGINEERING

Stephen L. Mayo
William K. Bowes Jr. Leadership Chair

Dianne Newman
Executive Officer for Molecular Biology

Markus Meister
Executive Officer for Neurobiology

Michael Elowitz
Executive Officer for Biological Engineering

Thanos Siapas
Executive Officer for Computation and Neural Systems

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, Ph.D.
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

Professors

Ralph Adolphs, Ph.D.
Bren Professor of Psychology, Neuroscience, and Biology; Allen V. C. Davis and Lenabelle Davis Leadership Chair, Caltech Brain Imaging Center; Director, Caltech Brain Imaging Center

John M. Allman, Ph.D.
Frank P. Hixon Professor of Neurobiology

Richard A. Andersen, Ph.D.
James G. Boswell Professor of Neuroscience; T&C Brain-Machine Interface Leadership Chair; Director, T&C Brain-Machine Interface Center

David J. Anderson, Ph.D.[1]
Seymour Benzer Professor of Biology; Tianqiao and Chrissy Chen Institute for Neuroscience Leadership Chair; Director, Tianqiao and Chrissy Chen Institute for Neuroscience

Alexei A. Aravin, Ph.D.
Biology,

Frances H. Arnold, Ph.D.
Linus Pauling 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.
David Baltimore Professor of Biology

Marianne Bronner, Ph.D.
Albert Billings Ruddock Professor of Biology, Director of the Beckman Institute

Long Cai, Ph.D.
Biology and Biological Engineering

Judith L. Campbell, Ph.D.
Chemistry and Biology

David C. Chan, M.D., Ph.D.
Biology

Michael H. Dickinson, Ph.D.
Esther M. and Abe M. Zarem Professor of Bioengineering and Aeronautics

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

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[1] *Joint appointment with Howard Hughes Medical Institute*

752

Changhuei Yang, Ph.D.
Thomas G. Myers Professor of Electrical Engineering, Bioengineering, and Medical Engineering

Magdalena Zernicka-Goetz, Ph.D.
Bren Professor of Biology and Biological Engineering

Kai Zinn, Ph.D.
Howard and Gwen Laurie Smits Professor of Biology

Assistant Professors

Elizabeth J. Hong, Ph.D.
Clare Boothe Luce Assistant Professor of Neuroscience

Yuki Oka, Ph.D.
Biology

Joseph Parker, Ph.D.
Biology and Biological Engineering

Matt Thomson, Ph.D.
Computational Biology; Investigator, Heritage Medical Research Institute

David Van Valen, Ph.D.
Biology and Biological Engineering

Rebecca M. Voorhees, Ph.D.
Biology and Biological Engineering; Investigator, Heritage Medical Research Institute

Kaihang Wang, Ph.D.
Biology and Biological Engineering

Senior Research Associate Emeriti

Anne Chomyn, Ph.D.
Ellen G. Strauss, Ph.D.
R. Andrew Cameron, Ph.D.

Lecturers

Justin Bois, Ph.D.
Lindsay Bremner, Ph.D.
Andres Collazo, Ph.D.
Pamela Eversole-Cire, Ph.D.
Eric Hoopfer, Ph.D.
Julie Hoy, Ph.D.
Eugenia Khorosheva, Ph.D.
Sarah MacLean, Ph.D.
Danny Petrasek, M.D., Ph.D.
Carol Chace Tydell, D.V.M

Research Professors

Katalin Fejes Toth, M.D., Ph.D.
David M. Glover, Ph.D.
Akiko Kumagai, Ph.D.
Carlos Lois, M.D., Ph.D.
Isabelle S. Peter Lashgari Faghani, Ph.D.
Daniel A. Wagenaar, Ph.D.
Mary An-yuan Yui, Ph.D.

Research Assistant Professor

Alina Patke, Ph.D.

Senior Faculty Associate

Alice S. Huang, Ph.D.

Moore Distinguished Scholar

Andrew P. McMahon

Visiting Associates

Takuya Akashi, Ph.D.
Clare Baker, Ph.D.
Elaine L. Bearer, Ph.D., M.D.
William L. Caton III, M.D.
Tsui-Fen Chou, Ph.D.
Vasileios N. Christopoulos, Ph.D.
Raymond Deshaies, Ph.D.
Jordi Garcia-Ojalvo, Ph.D.
David Glover, Ph.D.
Ingileif Bryndis Hallgrimsdottir, Ph.D.
Elaine Hsiao, Ph.D.
Collin Kieffer, Ph.D.
Brian Lee, M.D., Ph.D.
Carmel Levitan, Ph.D.
Ye Li, Ph.D.
Stephen B. Liggett, M.D.
Charles Liu, M.D., Ph.D.
Adam Mamelak, Ph.D.
Uri Maoz, Ph.D.
John P. McCutcheon, Ph.D.
Eric Mjolsness, Ph.D.
Alina Patke, Ph.D.
Carmie Puckett Robinson, M.D.
Animesh Ray, Ph.D.
Carol W. Readhead, Ph.D.
Ueli Rutishauser, Ph.D.
Mohammad Hassan Abdelrahman Shehata, Ph.D.
Linda Ann Silveira, Ph.D.
Beth Stadtmueller, Ph.D.

753

[1] *Joint appointment with Howard Hughes Medical Institute*

Sheila Kitchen, Ph.D.
Erin Koch, Ph.D.
Theodora Koromila, Ph.D.
Ezgi Kunttas-Tatli, Ph.D.
Michael Lawson, Ph.D.
James Lee, Ph.D.
Katherine J. Leitch, Ph.D.
Lingyun Li, Ph.D.
Shan Li, Ph.D.
Ting Li, Ph.D.[1]
Yatang Li, Ph.D.
Yuwei Li, Ph.D.
Lu Liu, Ph.D.
Yuxi Liu, Ph.D.
Francisco Luongo, Ph.D.
Ke Lyu, Ph.D.
Frank Macabenta, Ph.D.
Vishal Maingi, Ph.D.
Megan Martik, Ph.D.
Tara Mastro, Ph.D.
Darcy McRose, Ph.D.
Lauren Ann Metskas, Ph.D.
Erick Moen, Ph.D.
George Mountoufaris, Ph.D.
Brittany D. Needham, Ph.D.
Susan Newcomb, Ph.D.
Hon Man Alex Ng, Ph.D.
Aaron L. Nichols, Ph.D.
William Nicolas, Ph.D.[1]
Maria Ninova, Ph.D.
Sumner Norman, Ph.D.
Vasileios Ntranos, Ph.D.
Georg Oberhofer, Ph.D.
Aki Ohdera, Ph.D.
Noah Ollikainen, Ph.D.
Youcef Ouadah, Ph.D.
Ariana Peck, Ph.D.
Nicolas Pelaez Restrepo, Ph.D.
Michael Louis Piacentino, Ph.D.
Tino Pleiner, Ph.D.
Michal Polonsky, Ph.D.
Allan Herman Pool, Ph.D.
Mu Qiao, Ph.D.
Nitzan Razin, Ph.D.
John Elliott Robinson, Ph.D., M.D.
Ivo Ros, Ph.D.
Yuan Ruan, Ph.D.[1]
Satya Prakash Rungta, Ph.D.
Sofia Sakellardi, Ph.D.
Luis Oscar Sanchez Guardado, Ph.D.
Dominic Scalise, Ph.D.
Henry L. Schreiber IV, Ph.D.
Catherine Schretter, Ph.D.
Kevin Shan, Ph.D.
Liang She, Ph.D.
Pei Yin Shih, Ph.D.
Boyoung Shin, Ph.D.
Kyobi Skutt-Kakaria, Ph.D.
Tianqi Song, Ph.D.
Melanie A. Spero, Ph.D.
Argyrios Stefanos Stagkourakis, Ph.D.
Vincent Andrew Stepanik, Ph.D.
Jingjing Sun, Ph.D.

Sai Sun, Ph.D.
Calle Valentine Svensson, Ph.D.
Akshay Tambe, Ph.D.
Qing Tang, Ph.D.
Carsten Tischbirek, Ph.D.
Huy Ngoc Steven Tran, Ph.D.
Jonathan Exiquio Valencia, Ph.D.
Chelsey VanDrisse, Ph.D.
Amit Vinograd, Ph.D.
Bo Wang, Ph.D.
Han Wang, Ph.D.
Yuhang (Steven) Wang, Ph.D.
Brandon Weissbourd, Ph.D.[1]
Joseph Wekselblatt, Ph.D.
Jin Xu, Ph.D.
Shuwa Xu, Ph.D.
Takako Yamamoto (Ichiki), D.D.S, Ph.D.
Qing Yao, Ph.D.
Hanako, Yashiro, Ph.D.
An Zhang, Ph.D.
Carey Zhang, Ph.D.
Rong Wei Zhang, Ph.D.
Yandong Zhang, Ph.D.
Wei Zhao, Ph.D.
Yuan Zhao, Ph.D.

Visitors

Libera Berghella, Ph.D.
Ailin Buzzi, Ph.D.
Andrea Cerase, Ph.D.
Andrew Cox, Ph.D.
Constantine Evans, Ph.D.
Kirsten Frieda, Ph.D.
Danielle Grotjahn, Ph.D.
Jan Kaminski, Ph.D.
Alexei Kotov, Ph.D.
Anton Kuzmenko, Ph.D.
Davide Mariani, Ph.D.
Jasna Markovac, Ph.D.
Michael Marks, Ph.D.
John Brian McManus, Ph.D.
Alex Nisthal, Ph.D.
Barry Olafson, Ph.D.
David J. Sherman, Ph.D.
Amol V. Shivange, Ph.D.
Berna Sozen, Ph.D.
Noelle Stiles, Ph.D.
Takashi Suegami, Ph.D.
Wei Yuan Yang, Ph.D.

Trustees, Administration, Faculty

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

Julia Kornfield
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, William K. Bowles Jr. Leadership Chair, Division of Biology and Biological Engineering

Thomas F. Miller III, Ph.D.
Chemistry

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758

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759

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764

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765

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767

768

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772

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773

774

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779

780

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782

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783

786

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789

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791

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793

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797

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809

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815

816

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819

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823

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827

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829

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835

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845