Caltech Catalog

2009—2010

2009–10

Caltech Catalog

California Institute of Technology
Pasadena, California 91125
626/395-6811

September 2009

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.

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

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ACADEMIC CALENDAR 2009–10

FIRST TERM 2009

September 20–22
International student orientation

September 23–27
New student check-in and orientation

September 29
Beginning of instruction—8 a.m.

September 30
Undergraduate Academic Standards and Honors Committee—9 a.m.

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

October 28–November 3
Midterm examination period

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

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

November 19–December 4
Registration for second term, 2009–10

November 20
Last day for admission to candidacy for the degrees of Master of Science and Engineer

November 26–27
Thanksgiving (Institute holiday)

December 4
Last day of classes
Last day to register for second term, 2009–10, without a $50 late fee

December 5–8
Study period

December 9–11*
Final examinations, first term, 2009–10

December 11
End of first term, 2009–10

December 12–January 3
Winter recess

**First due date for final examinations*

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

December 25–28
Christmas (Institute holiday)

December 29–31
Special release days

January 1
New Year holiday (Institute holiday)

SECOND TERM 2010

January 4
Beginning of instruction—8 a.m.

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

January 18
Martin Luther King Day (Institute holiday)

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

February 3–9
Midterm examination period

February 15
Presidents' Day (Institute holiday)

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

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

February 25–March 10
Registration for third term, 2009–10

March 10
Last day of classes
Last day to register for third term, 2009–10, without a $50 late fee

March 11–14
Study period

March 15–17*
Final examinations, second term, 2009–10

March 17
End of second term, 2009–10

March 18–28
Spring recess

March 24
Instructors' final grade reports due—9 a.m.

THIRD TERM 2010

March 29
Beginning of instruction—8 a.m.

March 30
Undergraduate Academic Standards and Honors Committee—9 a.m.

April 16
Last day for adding courses and removing conditions and incompletes

April 28–May 4
Midterm examination period

May 10
Midterm deficiency notices due—9 a.m.
Last day for seniors to remove conditions and incompletes

May 14
Last day for scheduling examinations for the degrees of Doctor of Philosophy and Engineer

May 19
Last day for dropping courses, exercising pass/fail option, and changing sections

May 20–June 4
Registration for first term, 2010–11, and for summer research

May 28
Last day of classes—seniors and graduate students
Last day for presenting theses for the degrees of Doctor of Philosophy and Engineer

May 29–June 1
Study period for seniors and graduate students

May 31
Memorial Day (Institute holiday)

June 2–4*
Final examinations for seniors and graduate students, third term, 2009–10

June 4
Last day of classes—undergraduates
Last day to register for first term, 2010–11, without a $50 late fee

**First due date for final examinations*

June 5–8
Study period for undergraduates

June 7
Instructors' final grade reports due for seniors and graduate students—9 a.m.

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

June 9–11*
Final examinations for undergraduates, third term, 2009–10

June 11
Commencement—10 a.m.
End of third term, 2009–10

June 16
Instructors' final grade reports due for undergraduates—9 a.m.

June 23
Undergraduate Academic Standards and Honors Committee—9 a.m.

July 2–5
Independence Day (Institute holiday)

September 6
Labor Day (Institute holiday)

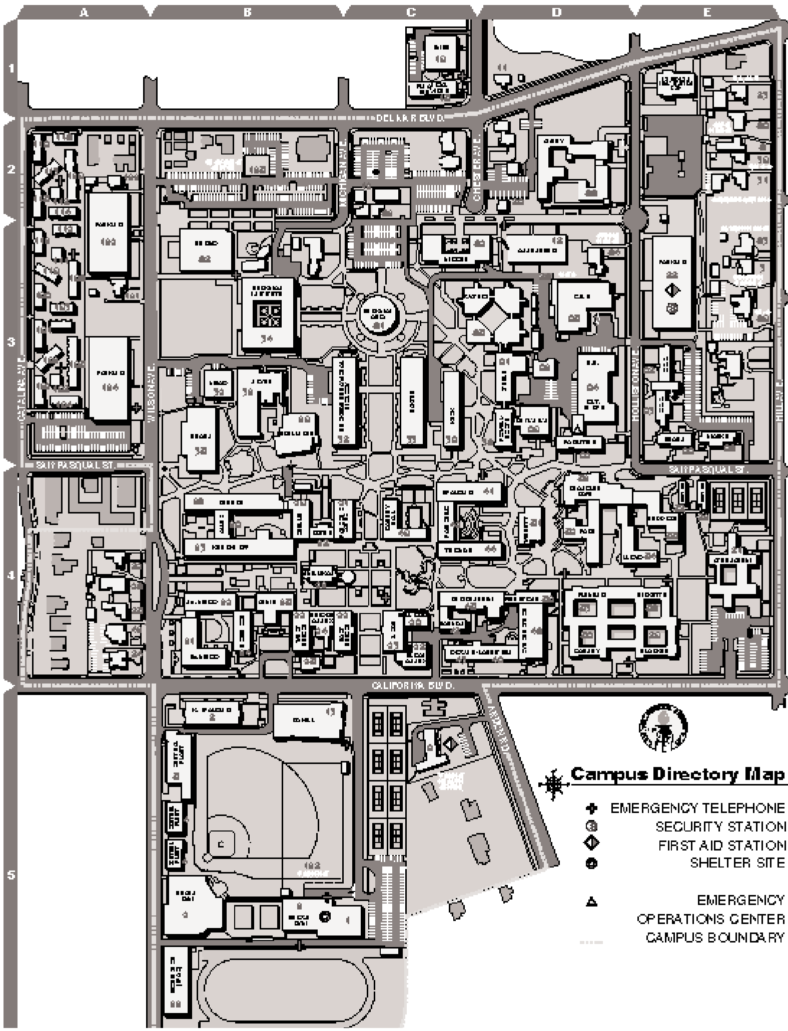
FIRST TERM 2010–11

September 19–21
International student orientation

September 21–26
New-student check-in and orientation

September 27
Beginning of instruction—8 a.m.

September 28
Undergraduate Academic Standards and Honors Committee—9 a.m.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DELMAR BLVD.
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General Information

INTRODUCTION

The California Institute of Technology is an independent, privately supported university, whose educational mission has not changed since it was stated by the original trustees on November 29, 1921: "To train the creative type of scientist or engineer urgently needed in our educational, governmental, and industrial development."

Its mission in research was expressed by President Emeritus Thomas E. Everhart in his 1988 inaugural address: "There need to be a few places that look ahead and still dare to do the most ambitious things that human beings can accomplish. Caltech still has that ambition and that daring."

Caltech conducts instruction at both the undergraduate and graduate levels and, including its off-campus facilities, is one of the world's major research institutions. Its mission to train creative scientists and engineers is achieved by conducting instruction in an atmosphere of research, accomplished by the close contacts between a relatively small group of students (approximately 900 undergraduate and 1,200 graduate students) and the members of a relatively large faculty (296 professorial faculty, 60 research faculty, and 600 postdoctoral scholars). "Caltech has achieved international influence far disproportionate to its size," according to *Time* magazine.

Caltech's educational objective is to provide an outstanding education that prepares students to become world leaders in science, engineering, academia, business, and public service.

The Institute's educational outcomes are as follows.

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

The Institute is organized into six divisions: Biology; Chemistry and Chemical Engineering; Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics and Astronomy. It is accredited by the Accrediting Commission for Senior Colleges and Universities of the Western Association of Schools and Colleges.

Undergraduate Program

Caltech offers a four-year undergraduate course with options available in applied and computational mathematics; applied physics; astrophysics; bioengineering; biology; business economics and management; chemical engineering; chemistry; computer science; economics; electrical engineering; engineering and applied science; English; geobiology; geochemistry; geology; geophysics; history; history and philosophy of science; independent studies; mathematics; mechanical engineering; philosophy; physics; planetary science; and political science. Each leads to the degree of Bachelor of Science.

All options require students to take courses in biology, chemistry, humanities, mathematics, physics, and the social sciences. Course work is rigorous and students are encouraged to participate in research. The undergraduate program is thus designed to provide an intensive exposure to a wide spectrum of intellectual pursuits.

Near the end of the first year, students select an option, and during the second year they begin to specialize. However, the major concentration in chosen fields and professional subjects occurs during the third and fourth years.

Caltech also encourages a reasonable participation in extracurricular activities, which are largely managed by the students themselves. Three terms of physical education are required, and intercollegiate and intramural sports are encouraged.

In short, every effort is made to provide undergraduate students with well-rounded, integrated programs that will not only give them sound training in their professional fields, but that will also develop character, intellectual breadth, and physical well-being.

Graduate Program

Graduate students constitute approximately 57 percent of the total student body at Caltech. Jointly engaged in research problems with faculty members, they contribute materially to the general atmosphere of intellectual curiosity and creative activity generated on the Institute campus.

Caltech offers courses leading to the degree of Master of Science, which normally involves one year of graduate work; the degree of Engineer in certain branches of engineering, with a minimum of two years; and the degree of Doctor of Philosophy. In all the graduate work, research is strongly emphasized, not only because of its importance in contributing to the advancement of science and thus to the intellectual and material welfare of humankind, but also because research activities add vitality to the educational work of Caltech.

The graduate options are aerospace, applied and computational mathematics, applied mechanics, applied physics, astrophysics, behavioral and social neuroscience, biochemistry and molecular biophysics, bioengineering, biology, chemical engineering, chemistry, civil engineering, computation and neural systems, computer science, control and dynamical systems, electrical engineering, environmental science and engineering, geological and planetary sciences, materials science, mathematics, mechanical engineering, physics, and social science.

Postdoctoral and Senior Postdoctoral Scholars

Postdoctoral scholars form a vital part of the research community at Caltech and JPL. They advance knowledge through research and scholarship in science and technology; add to their own experience and education; and contribute to the education of Caltech undergraduates and graduate students. Postdoctoral scholars on campus always work under the close supervision of one or more Caltech professorial faculty members. In virtually all circumstances they must have an earned doctorate from a duly accredited institution. Upon arrival at the Institute, postdoctoral scholars should call the Postdoctoral Scholar Services office in Human Resources, (626) 395-3300, to make an appointment to activate their positions according to the terms and conditions of their letter.

Betty and Gordon Moore Distinguished Visitors

The Moore Distinguished Visitors program brings to the Caltech campus scientists, scholars, technologists, and artists of great distinction or of great promise. Through this program, Caltech faculty and students and the Moore Distinguished Visitors will have the opportunity to inform, inspire, and invigorate one another through discussions, seminars, lectures, and research. Appointments will be made in all academic divisions, and will normally last from two to nine months.

HISTORICAL SKETCH

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

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

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

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

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

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

The great period of the Institute's life began, then, under the guidance of three men of vision—Hale, Noyes, and Millikan. They were distinguished research scientists who soon attracted graduate students. In 1920 the enrollment was nine graduate students and 359 undergraduates with a faculty of 60; a decade later there were 138 graduate students, 510 undergraduates, and a faculty of 180. At the present time there are about 900 undergraduates, 1,100 graduate students, and 900 faculty (including postdoctoral fellows).

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

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

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

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

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

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

In 1928 George Ellery Hale and his associates at the Mount Wilson Observatory developed a proposal for a 200-inch telescope and attracted the interest of the General Education Board in providing $6,000,000 for its construction. The Board proposed that the gift be made, and Caltech agreed to be responsible for the construction and operation. The huge instrument was erected on Palomar Mountain. Teaching and research in astronomy and astrophysics thus became a part of the Caltech program.

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

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

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

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

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

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

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

In October 1997, Dr. David Baltimore assumed the presidency of the Institute. One of the world's leading biologists, he received the 1975 Nobel Prize for his work in virology. Previously the Ivan R. Cottrell Professor of Molecular Biology and Immunology at MIT and founding director of its Whitehead Institute for Biomedical Research, Baltimore had also served as president of Rockefeller University, where he earned his doctorate in 1964. He played a pivotal role in creating a consensus on national science policy regarding recombinant DNA research, served as chairman of the National Institute of Health AIDS Vaccine Research Committee, and in 1999 was awarded the National Medal of Science by President Clinton.

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

Dr. Jean-Lou Chameau became Caltech's eighth president on September 1, 2006. The former provost and vice president for academic affairs at the Georgia Institute of Technology, he was also a Georgia Research Alliance Eminent Scholar and the Hightower Professor, and he earlier served as dean of the Georgia Tech College of Engineering, the largest in the country. Chameau had focused on making Georgia Tech a worldwide model for interdisciplinary education and research, innovation, and entrepreneurship, and for the promotion of these activities as a catalyst for economic development. He received his undergraduate education in France and his Ph.D. in civil engineering from Stanford University, and is particularly interested in sustainable technology, environmental geotechnology, soil dynamics, earthquake engineering, and liquefaction of soils.

Since coming to the Institute, Chameau has overseen the conclusion of the largest fund-raising campaign in Caltech's history and the construction of the Cahill Center for Astronomy and Astrophysics, the Annenberg Center for Information Science and Technology, and the Schlinger Laboratory for Chemistry and Chemical Engineering. Known for his commitment to developing multidisciplinary talent in faculty and students, Chameau has placed strong emphasis on improving the educational experience of students, on increasing diversity, and on fostering research, entrepreneurial, and international opportunities for faculty and students.

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

Caltech has more than 22,000 living alumni all over the world, many of them eminent in their fields of engineering, science, law, medicine, academe, and entrepreneurship.

Caltech Nobel Laureates

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

Edward B. Lewis, Ph.D. ’42	physiology or medicine	1995
Douglas D. Osheroff, B.S. ’67	physics	1996
Robert C. Merton, M.S. ’67	economics	1997
* Ahmed H. Zewail	chemistry	1999
Leland H. Hartwell, B.S. ’61	physiology or medicine	2001
Vernon L. Smith, B.S. ’49	economics	2002
* Hugh David Politzer	physics	2004
* Robert H. Grubbs	chemistry	2005

* *In residence*

Caltech Crafoord Laureates

* Gerald J. Wasserburg	geochemistry	1986
Allan R. Sandage, Ph.D. ’53	astronomy	1991
Seymour Benzer	biosciences	1993
* Don L. Anderson, M.S. ’58, Ph.D. ’62	geosciences	1998
James E. Gunn, Ph.D. ’66	astronomy	2005

* *In residence*

BUILDINGS AND FACILITIES

On-Campus Buildings

Gates and Crellin Laboratories of Chemistry: first unit, 1917; second unit, 1927; third unit, 1937. The first two units were the gifts of Messrs. C. W. Gates and P. G. Gates of Pasadena; the third unit was the gift of Mr. and Mrs. E. W. Crellin of Pasadena. Gates (first unit), which was retired after suffering extensive damage in the 1971 earthquake, was rebuilt in 1983 as the Parsons-Gates Hall of Administration. **The Arnold and Mabel Beckman Laboratory of Chemical Synthesis,** 1986, occupying portions of Crellin Laboratory (as well as portions of Church Laboratory for Chemical Biology), was built with funds provided by the Arnold and Mabel Beckman Foundation.

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

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

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

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

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

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

Undergraduate Houses, 1931. With the support of many individuals, including alumni Alexander Lidow, Richard Beatty, and Ray Sidney, these houses were restored. They reopened in 2007.

Blacker House. The gift of Mr. and Mrs. R. R. Blacker of Pasadena.

Dabney House. The gift of Mr. and Mrs. Joseph B. Dabney of Los Angeles.

Fleming House. Built with funds provided by some 20 donors and named in honor of Mr. Arthur H. Fleming of Pasadena, president of the Board of Trustees, 1917–33.

Ricketts House. The gift of Dr. and Mrs. Louis D. Ricketts of Pasadena.

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

Henry M. Robinson Laboratory of Astrophysics, 1932. Built with funds provided by the International Education Board and the General Education Board, and named in honor of Mr. Henry M. Robinson of Pasadena, member of the Board of Trustees, 1907–37, and of the Executive Council of the Institute. To be renovated in 2009 and 2010 and renamed the Linde + Robinson Laboratory.

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

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

Franklin Thomas Laboratory of Engineering: first unit, 1945; second unit, 1950. Funds for the first unit were allocated from the Eudora Hull Spalding Trust with the approval of Mr. Keith Spalding, trustee. Named in honor of Dean Franklin Thomas, professor of civil engineering and first chair of the Division of Engineering, 1924–45.

Alumni Swimming Pool, 1954. Provided by the Alumni Fund through contributions from the alumni of the Institute.

Scott Brown Gymnasium, 1954. Built with funds provided by the trust established by Mr. Scott Brown of Pasadena and Chicago, who was a member and director of the Caltech Associates.

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

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

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

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

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

Undergraduate Houses, 1960. Built with funds provided by the Lloyd Foundation and other donors.

Lloyd House. Named in memory of Mr. Ralph B. Lloyd and his wife, Mrs. Lulu Hull Lloyd, of Beverly Hills. He was a member of the Board of Trustees, 1939–52.

Page House. Named in honor of Mr. James R. Page of Los Angeles, a member of the Board of Trustees, 1931–62, and chairman, 1943–54.

Ruddock House. Named in honor of Mr. Albert B. Ruddock of Santa Barbara, a member of the Board of Trustees, 1938–71, and chairman, 1954–61.

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

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

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

Graduate Houses, 1961:

Braun House. Built with funds provided by the trustees of the Carl F Braun Trust Estate, in his memory.

Marks House. The gift of Dr. David X. Marks of Los Angeles.

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

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

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

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

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

Central Engineering Services Building, 1966.

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

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

Central Plant, 1967.

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

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

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

The Earle M. Jorgensen Laboratory of Information Science, 1971. Built with the gift of Mr. and Mrs. Earle M. Jorgensen, with additional funds provided by the Booth-Ferris Foundation and other private donors. Mr. Jorgensen was a member of the Board of Trustees, 1957–99.

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

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

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

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

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

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

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

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

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

Wilson Avenue North Parking Structure, 1987.

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

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

Holliston Avenue Parking Structure/Satellite Utility Plant, 1993.

The Gordon and Betty Moore Laboratory of Engineering, 1996. Built with funds provided by Dr. and Mrs. Gordon Moore. Dr. Moore is an alumnus and chairman emeritus of the Board of Trustees.

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

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

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

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

Wilson Avenue South Parking Structure, 1999.

Center for Student Services, the Keck Wing, 2000. Originally the Keck Graduate House, built with funds provided by the William M. Keck, Jr., Foundation, 1961. **Center for Student Services, the Mosher-Jorgensen Wing,** 2002. Originally the Mosher-Jorgensen Graduate House, built with funds provided by Mr. Samuel B. Mosher and Mr. Earle M. Jorgensen, both of Los Angeles. Mr. Jorgensen was a member of the Board of Trustees, 1957–99.

Financial Services Building, 2000.

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

California Parking Structure, 2005.

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

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

Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering, construction to be completed in 2009. Built with funds provided by alumnus Warren Schlinger and his wife, Katharine, a former Caltech employee; and other private donors.

Off-Campus Facilities

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

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

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

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

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

Submillimeter Observatory, 1986, Mauna Kea, Hawaii. Built with funds provided by the National Science Foundation and the Kresge Foundation.

W. M. Keck Observatory, Keck I (1991), Keck II (1996); Mauna Kea, Hawaii. Built with funds provided by the W. M. Keck Foundation. Site of the two 10-meter Keck Telescopes.

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

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

Beckman Institute

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

Center for Advanced Computing Research

The mission of the Center for Advanced Computing Research (CACR) is to ensure that Caltech is at the forefront of computational science and engineering (CSE). CSE is the practice of computer-based modeling, simulation, and data analysis for the study of scientific phenomena and engineering designs. Computer modeling and simulation make it possible to investigate regimes that are beyond current experimental capabilities and to study phenomena that cannot be replicated in laboratories, such as the evolution of the universe. The results often suggest new experiments and theories. Computation is also essential for processing the flood of high-dimensional data generated by modern instruments.

CACR provides an environment that cultivates multidisciplinary collaborations. CACR researchers take an applications-driven approach and currently work with Caltech research groups in aerospace engineering, applied mathematics, astronomy, biology, engineering, geophysics, materials science, and physics. Center staff have expertise in data-intensive scientific discovery, physics-based simulation, scientific software engineering, visualization techniques, novel computer architectures, and the design and operation of large-scale computing facilities.

Industrial Relations Center

The Industrial Relations Center develops and offers programs on managing technology and innovation, improving the effectiveness of business operations, developing the leadership skills of technical professionals, and encouraging new business ventures. Courses and forums are presented on campus and are open to executives and managers in technology-based organizations, and Caltech students, faculty, and staff. Fees are waived for Caltech students who participate in the center's programs.

The center is located on campus at 383 South Hill Avenue. The latest calendar of programs or more information may be obtained by calling (626) 395-4041.

Libraries

The Caltech Library System (CLS) consists of a number of distributed library locations from which staff provide a high level of information service to support and facilitate the research and educational programs of the Institute. The Library's policies and many electronic resources, including the online catalog, are accessible from the CLS website at http://library.caltech.edu.

The CLS includes the astrophysics library; Dabney library for the Division of the Humanities and Social Sciences, which contains literature, art, philosophy, European, Asian, and ancient history monographs, and music CD collections; the geology library, with an extensive map collection; Millikan Memorial Library, which contains collections for biology, chemistry, mathematics, and physics, government documents, microforms, the humanities and social sciences journals, American history and social sciences monographs, along with library administration and the interlibrary-loan/document delivery services; the Sherman Fairchild Library of Engineering and Applied Science, which supports the environmental, aerospace, chemical and mechanical engineering, and applied physics and mathematics programs.

Collectively, the libraries subscribe to over 2,909 print journals and 27,262 electronic journals. They hold over 725,000 volumes, and have extensive collections of technical reports, government documents, and maps. The library electronic catalog includes records of print and nonprint materials held throughout the libraries, and active links to electronic resources, especially full-text online journals. Special services available through the libraries include document delivery, interlibrary loans, digitizing and archiving technical report collections, and the creation and archiving of electronic theses, dissertations, and other research papers.

UNDERGRADUATE RESEARCH

The Institute provides three principal avenues for undergraduate research: the Summer Undergraduate Research Fellowships (SURF) program, research courses for academic credit and senior theses, and research for pay under a faculty member's grant or contract. Students may combine these options, but they may not receive both pay and credit (at the same time) for the same piece of work. Students registering for a research course during the summer do not have to pay tuition.

Each division offers the opportunity for qualified students early in their careers to engage in research under the supervision of a faculty member. Most options offer undergraduate research courses in order to encourage participation, and students should consult listings and descriptions of opportunities. Students are encouraged to undertake research of such scope and caliber as to merit the preparation of a senior thesis. The requirements for such thesis research vary from option to option; individual option representatives should be consulted.

The Summer Undergraduate Research Fellowships (SURF) program provides continuing undergraduate students the opportunity to work on an individual research project in a tutorial relationship with a mentor, usually a member of the Caltech/JPL research community, but occasionally a faculty member at another college or university. Students write research proposals in collaboration with their mentors. Proposals and recommendations are reviewed by the SURF administrative committee, and awards are made on the basis of reviewer recommendation and available funding. The work is carried out during a 10-week period in the summer. Students may attend weekly seminars presented by members of the Caltech faculty and JPL technical staff and may participate in professional development workshops. At the conclusion of the summer, SURFers submit a written report describing the project, methods, and results of their work. On the third Saturday of October, students make oral presentations of their projects at SURF Seminar Day. About 20 percent of the students publish their work in the open scientific literature. In 2008, SURF students received awards of $6,000. Applications are available online at http://www.surf.caltech.edu and are due in mid-February. Awards are announced in early April. To be eligible, students must be continuing undergraduates and have a cumulative GPA of at least 2.0. Students must complete the third quarter at Caltech (or at another school under a program approved by a dean). Students must be eligible for fall term registration as of the end of the June Undergraduate Academic Standards and Honors (UASH) Committee reinstatement meeting and must not be on medical leave or under disciplinary sanction.

For further information regarding this program, contact the Student-Faculty Programs Office, 08 Parsons-Gates, (626) 395-2885, sfp@caltech.edu. Visit the Student-Faculty Programs website at http://www.sfp.caltech.edu for more information on SURF and other programs.

STUDENT LIFE

Undergraduate Student Houses

Seven of the eight undergraduate student houses are situated on both sides of the Olive Walk near the southeastern end of the campus. The original four—Blacker, Dabney, Fleming, and Ricketts—were built in 1931 from the plans of Mr. Gordon B. Kaufmann, in the Mediterranean style to harmonize with the adjacent Athenaeum. The other three, designed by Smith, Powell and Morgridge, were completed in 1960, and are named Lloyd, Page, and Ruddock.

Each of the houses is a separate unit with its own dining room and lounge, providing accommodations for between 65 and 100 students, depending on the house. Each has its own elected officers; a long history of self-governance gives students a great deal of influence over their living environments. Each house has a resident associate, typically a graduate student.

In addition to the student houses, the Institute maintains three apartment buildings, Marks/Braun House, and a number of off-campus houses. Typically two or three students share an apartment. Depending upon size, the off-campus houses have a capacity of four to ten students. These residences are all within a short walk of the campus and offer students greater privacy, a different lifestyle, and the opportunity to prepare their own meals.

Application for rooms in student housing may be made through Institute Housing, Mail Code 160-86, California Institute of Technology, Pasadena, CA 91125, or at http://www.housing.caltech.edu.

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.

Avery House

Made possible by a gift from trustee R. Stanton Avery, this innovative residential complex was designed by Moore, Ruble, Yudell and completed in September 1996. Located at the north end of the campus, Avery House has a resident associate and rooms for about 110 undergraduates and 15 graduate students, in addition to three faculty apartments. Its dining facilities, meeting rooms, lounges, and library are designed to encourage informal faculty-student interaction and to attract all members of the campus community to join in this interaction. Avery House hosts programs and social events that facilitate involvement between residents, faculty in residence, Avery associate, and visitors to the campus.

Avery House began accepting freshmen in 2005, after which it became fully integrated into the undergraduate house system as the eighth house.

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 more 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.

Interhouse Activities
The president of each undergraduate house represents that house on the Interhouse Committee (IHC). While the eight houses are generally autonomous, the IHC exists to ensure that conflicts between houses do not develop and to deal with matters that affect the houses in general. In particular, the IHC is responsible for the selection process by which the houses choose their new members.

In conjunction with the athletic department, the IHC conducts two intramural sports programs: the Interhouse and Discobolus trophy competitions. (These are described below under *Athletics*.) Other interhouse activities include an annual eight-house party called Interhouse.

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. 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
Caltech supports a well-rounded program of competitive athletics. As a member of the NCAA Division III and the Southern California Intercollegiate Athletic Conference, Caltech carries out intercollegiate competition in nine men's sports and eight women's sports, with teams such as Claremont-Mudd-Scripps, LaVerne, Occidental, Pomona-Pitzer, Cal Lutheran, Redlands, and Whittier. Individual athletes and teams who distinguish themselves in conference competition earn the privilege of participating in NCAA regional and national championships.

Caltech also sponsors vigorous programs of club sports and intramural competition. Club sports include rugby, ultimate Frisbee, ice hockey, and men's volleyball and soccer. Intramural competition consists of residence house teams battling for championships (and bragging rights) in flag football, soccer, swimming, ultimate Frisbee, basketball, volleyball, tennis, track and field, and softball. Thirty percent of Caltech undergraduates participate in intercollegiate athletics, and over 80 percent participate in some form of organized athletic competition each year.

Outdoor athletic facilities include an all-weather running track, a soccer field, a baseball diamond, six tennis courts, and two 25-yard swimming pools. Indoor facilities include two full-size gymnasia for basketball, volleyball, and badminton; four racquetball courts; two squash courts; a 4,000-square-foot weight room; and a large multipurpose room for dance/aerobics, fencing, and martial arts.

ASCIT

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

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

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

Graduate Student Council

The graduate student body forms the membership of a corporation known as the Graduate Student Council, or GSC. Governed by a board of directors, consisting of graduate student representatives from different graduate options, the GSC provides funding for student clubs, publishes a monthly newsletter, and organizes or subsidizes various campus events. Annual events include New Student Orientation activities, and Gradiators, a fun-filled summer day of unusual games. *The Technique*, an information guide for graduate-student life off and on campus, is published by the GSC. The GSC also organizes monthly social hours, the GSC Teaching and Mentoring Awards, and the Everhart Lecture Series, which honors outstanding graduate student speakers, and is active in campus affairs, with graduate student representatives on many faculty standing committees.

Honor System

The Honor System, embodied in the phrase "No member shall take unfair advantage of any member of the Caltech community," is the fundamental principle of conduct for all students. More than merely a code applying to conduct in examinations, it extends to all phases of campus life. It is the code of behavior governing scholastic and extracurricular activities, relations among students, and relations between students and faculty. The Honor System is the outstanding tradition of the student body, which accepts full responsibility for its operation. The Board of Control, which is composed of elected student representatives, is charged with monitoring the Honor System for undergraduates, while the Graduate Review Board performs the same function for graduate students. The Conduct Review Committee, composed of students, faculty, and staff, also considers cases involving the Honor System and Institute policies. Suspected violations are reported to the appropriate board, which conducts investigations and hearings with strict confidentiality. If necessary, recommendations for actions are made to the deans.

Student Body Publications

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

Performing and Visual Arts Activities

The Institute provides qualified directors and facilities for various choral music groups, a concert band, a jazz band, a symphony orchestra (jointly with Occidental College), numerous chamber music ensembles, guitar classes, a theater program, and a variety of art classes. These activities are centered in the Music and Theater Arts Houses on Hill Avenue along the eastern edge of campus. Performances are held mainly in Dabney Lounge and Ramo Auditorium.

Student Societies and Clubs

The Institute has more than 70 societies and clubs covering a wide range of interests. The American Chemical Society, the American Institute of Chemical Engineers, the American Society of Mechanical Engineers, and the Society of Women Engineers all maintain active student branches. There is a chapter of the National Society of Black Engineers, and the Caltech Latino Association of Students in Engineering and Science is a chapter of the Society of Hispanic Engineers.

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

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

Student Shop

The student shop is housed in the Physical Plant complex. It is equipped by the Institute, largely through donations, and is operated by the students. Here qualified students may work on private projects that require tools and equipment not otherwise available. All students are eligible to apply for membership in the student shop; applications are acted on by a governing committee of students. Members not proficient in power tools are limited to hand tools and bench work; however, instruction in power tools is given as needed. Yearly dues are collected to provide for maintenance and replacement.

The Caltech Y

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

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

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

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

STUDENT HEALTH

Medical Examination
Before initial registration, each applicant is required to submit a Report of Medical History and Physical Examination on a form that is sent at the time of notification of admission. Students who have been absent from the Institute for one term or more may also be required to submit this report.

Student Health Services
The Archibald Young Health Center provides the following services for undergraduate and graduate students and their spouses enrolled in the Spouse Program: (1) office consultation and treatment of most medical problems by physicians and nurse practitioners (physician visits by appointment only and at prescribed hours); (2) referral to specialists; (3) laboratory tests and some radiology tests as ordered by the medical staff; (4) women's health services, including annual Pap and contraceptive needs; (5) sexual health concerns, including HIV and STD screening; (6) routine medications, common vaccinations, prescription drugs, and other supplies

at cost. A variety of health education handouts are also available. For more information, visit the health center webpage at http://www.healthcenter.caltech.edu.

Student Counseling Service

A staff of mental health professionals provides individual, group, and crisis counseling to undergraduates and graduates at no cost. Students are seen at the center with various concerns, such as depression, stress, grief, relationship difficulties, and self-esteem issues, among others. The center also offers workshops and training on psychologically related topics, a health-education program, psychiatric consultation, and referrals to other professionals in the community. Counseling sessions are confidential.

Health Education

As a joint service of the counseling and health centers, the health educator offers health education programs designed to enhance students' personal development and academic achievement. Program topics include stress management, general health and wellness, nutrition, alcohol and other drug use, and sexual health. Confidential, drop-in counseling hours are available. For additional information, visit http://www.healtheducation.caltech.edu.

Student Health Insurance

In addition to services provided by the Health and Counseling Centers, all currently enrolled degree-seeking Caltech students are enrolled in a comprehensive medical insurance plan through Caltech. Students have the option to waive Caltech's medical coverage provided they show proof of other adequate coverage. The Caltech student health plan covers (with deductible and copay) hospital and surgical costs, as well as the cost of outpatient treatment for injury, illness, and psychotherapy. Students may continue coverage under the Caltech student health plan during the entire time they are enrolled as degree-seeking Caltech students.

Medical Coverage of Dependents

A student's spouse and all unmarried dependent children under 19 years of age are eligible to purchase coverage under the medical insurance plan. In addition, student spouses may enroll for a modest fee in a plan that makes them eligible for all services offered at the Health Center. Children are not eligible for these services. Application for dependents' insurance should be made at the time of registration for any one school term. Rates for dependents' coverage are available at the Benefits Office in Human Resources.

Medical Responsibility of the Student

The responsibility for securing adequate medical attention in any contingency, whether emergency or not, is solely that of the student, whether the student is residing on or off campus. Apart from providing the opportunity for consultation and treatment at the Health Center as already described, the Institute bears no responsibility for providing medical attention.

Any expenses incurred in securing advice and attention in any case are entirely the responsibility of the student, except as already specified. Students should carry their medical insurance cards with them at all times. If they are covered under the Caltech student health plan, they should contact the student health plan insurance carrier to inquire about reimbursement for services received. If they are covered under another plan, they should contact their service provider for details on coverage and reimbursement of services.

CAREER DEVELOPMENT

Career Services

The Career Development Center (CDC) provides assistance to students, postdoctoral scholars, and alumni in the areas of career and life planning and employment. Personal assistance is available in career choice, résumé preparation, interviewing, graduate school application, and job search strategies. Career and vocational interest tests can also be taken.

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

CDC Online

The CDC's home page contains information about the center's programs and activities, as well as links to career, educational, and employment resources nationwide. The URL is http://www.career.caltech.edu.

Premedical and Graduate School Advising

Students planning to apply to medical school can make use of many resources and individual counseling in the CDC. Medical school catalogs and statistical information on successful Caltech medical school matriculants are among the materials available. Students can obtain relevant medical research experience, and there is a comprehensive list of available health-related volunteer opportunities. Counselors can help students throughout the process from freshman year to graduation, and will work closely with students to help ensure their success.

We encourage students planning to apply to graduate school and other professional programs to plan ahead. The CDC provides many resources for these programs. (See also pages 189 and 292–293.)

On-Campus Recruiting Program
Through the on-campus recruiting program, employment interviews are arranged with companies that seek full-time employees pursuing B.S., M.S., Eng., or Ph.D. degrees. All graduating students, Caltech postdoctoral scholars, and recent alumni are eligible to participate.

Career Days
Each year in October and February, companies send representatives to campus for a day of informal discussion with students on internship and employment opportunities. Most bring informative displays and literature, and many of the representatives are themselves Caltech alumni. Ph.D.'s and postdoctoral scholars also find organizations that address special considerations of researchers with doctoral degrees.

Career Library
The library contains information on college, graduate, and professional schools, scholarship information, company literature, employer directories, career literature, audio-visual resources, and access to Web-based data.

Work-Study and Employment Listings
Job listings are maintained in the Career Library and through NACElink Network for students seeking full-time, part-time (including tutoring positions), or work-study employment. Part-time employment provides students with the opportunity to help finance their education and to gain relevant work experience. (See also Student Employment, page 160.)

Internships
The CDC office provides opportunities for students at all levels to work in private industry, government laboratories, educational institutions, and other nonprofit agencies. Many of the advertised positions are with Caltech alumni.

Students are encouraged to see a career counselor to develop summer work interests that will support or complement their long-term career objectives. The CDC provides job search assistance including résumé preparation, mock interview training, and evaluation of offers consistent with goals. Application times for specific positions may be as early as October or as late as May. Many employers, eager to hire Caltech students, provide or supplement transportation and housing as part of their employment package.

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

Annual Report
The center surveys all graduating students and compiles a detailed annual report that provides information on the plans of graduating

students. Included are lists of graduate and medical schools chosen, companies that recruited on campus, and industry and academic salaries offered and accepted. (The report is available online at http://www.career.caltech.edu.)

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

Caltech graduates who accept industry positions consistently receive salaries in the top quartile nationally.

CALTECH ALUMNI ASSOCIATION

The mission of the Association is to promote the interests of Caltech in setting a world standard of academic excellence by strengthening the ties of goodwill and communication between the Institute, its alumni, and current students, and by maintaining programs to serve alumni needs. These programs include

- Alumni College, a two-day lecture series focused on one theme, with Caltech faculty as featured speakers;
- Seminar Day, a day of lectures, exhibits, and social events held on campus;
- reunions by class year and student house;
- travel/study programs worldwide;
- regional events around the world, many of which feature Caltech faculty.

The Association also supports student activities and organizations, and provides contact between alumni and students. Alumni volunteers play an important role for the Association by maintaining contact with prospective students and their families and by serving as networking resources to other alumni and to current students. Benefits of membership in the Alumni Association include a subscription to *Engineering & Science* magazine, an alumni e-mail account, discounts at the bookstore, and more. For more information, please see http://alumni.caltech.edu.

INTERNATIONAL STUDENT PROGRAMS

The Office of International Student Programs (ISP) is responsible for all immigration-related matters pertaining to students. In addition, ISP provides support services and programs that assist international students and their dependents in adjusting to life in the United States and in addressing any personal, academic, or other important issues that they may face during their stay at Caltech.

As the definitive immigration resource for international students, ISP disseminates information on the rules and regulations pertaining to all student visas. The office assists students with visa acquisition, employment authorization, extensions of stay, and any other immigration-related matters.

Both independently and in cooperation with various student organizations and Institute departments, ISP plans and promotes events that celebrate cultures and peoples of the world, address cross-cultural adjustment, and provide opportunities for international students to establish a sense of community at Caltech.

Each September, ISP hosts a weeklong orientation program that provides a comprehensive introduction to academic and social life at Caltech and in the United States. All incoming international students are required to participate in this program.

Further information about services, current programs, and U.S. immigration regulations pertaining to nonimmigrant students can be obtained by contacting the ISP staff at isp@caltech.edu.

For information on English-as-a-second-language courses for graduate students, please refer to the course listings of this catalog.

AUDITING COURSES

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

Auditing fees for nonacademic staff members may be covered by the Institute Tuition Support Plan. Auditing cards may be obtained in the Registrar's Office.

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

GRADES AND GRADING

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

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

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

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

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

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

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

Students receiving grades of E or I should consult with their instructors not later than the beginning of the next term in residence as to the work required and the time allowed. This time should, in most cases, coincide with the date fixed in the calendar for removal of conditions and incompletes (Add Day), and in fact if no other time is specified, this date will be assumed. Further, under no circumstances may the time for the completion of the work be extended for more than three terms in residence after the end of the term in which the grade of E or I was given. At the end of the specified time, unless there is a written request from the instructor to the contrary, or in any event at the time of graduation or at the end of three terms in residence, whichever occurs first, all E's and I's not otherwise reported will be changed to F. Grades of E and I shall not be considered in calculating a student's grade-point average.

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

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

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

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

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

Pass/Fail Grading: The following regulations apply:

- First-quarter and second-quarter freshmen receive pass/fail grades in all courses by virtue of their classification as freshmen by an admissions committee or, for students whose status after the first year is uncertain, by the Undergraduate Academic Standards and Honors Committee.
- Required laboratory courses will be graded P or F regardless of when they are taken, but these courses must be taken during the freshman or sophomore years.
- 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 office of the registrar

a completed Pass/Fail Course Selection Card not later than the last day for dropping courses.

- In courses with numbers 200 or greater that are not designated either "graded pass/fail" or "letter grades only," the instructor may decide separately for each student what class of grades to use.
- All research courses shall be designated "graded pass/fail." All reading courses, seminar courses, or other courses that do not have a formal class structure shall be designated "graded pass/fail" unless the option secures an exemption from the Curriculum Committee or the Graduate Studies Committee and from the Faculty Board.
- A grade on the pass/fail system should be P if it would have been a D or better on the letter grade system. (Note that there is no D- grade.) The standards of failure in courses in which only pass/fail grades are used should be the same as they would be if the course were letter graded.
- Any instructor may, at his or her discretion, specify prior to registration that his or her course, if not classified by the above regulations, is to be graded on a "letter grades only" basis or is to be graded pass/fail only, subject to possible review by the responsible option. The registrar must be notified of such specification two weeks before the beginning of registration. (Note: If the grading scheme is changed during the term, it is changed for everyone.)
- Each term any student may select, subject to such requirements as may be imposed by the option, two elective courses in which he or she is to be graded on a pass/fail basis if it is not designated as "letter grades only" and is not specifically required for the degree in his or her option. To make this election, a completed Pass/Fail Course Selection Card must be submitted to the Office of the Registrar on or before the last day for dropping courses that term. This election may be reversed or reinstated at any time before the deadline. The election must be approved and the card signed by the student's adviser. The instructor must be notified and should sign the card to indicate that this has been done; the instructor must allow any eligible student to make this election.
- Of the units offered to satisfy the requirements for the Bachelor of Science degree, no more than 90 may be in courses graded pass/fail because of the student's election.

Procedures for Resolving Disputes over Grading

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

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

NOTICES AND AGREEMENTS

Academic Records of Veterans

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

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

The grading system of the Institute is A (excellent) to F (failed). An A is equivalent to 4.0 and an F to 0.0. A student must maintain a grade-point average of 1.4 in any term and at least 1.9 in each full year 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 averages (1.4 for a given term or 1.9 for the year) is dismissed and must petition for reinstatement. A student may be reinstated by the Undergraduate Academic Standards and Honors Committee and, if so, is required to earn a 1.9 GPA during the immediately following term. The Veterans Administration is notified when a veteran is academically dismissed or is making unsatisfactory progress toward a degree. Since the Institute requires all students to carry a minimum full load that corresponds to 12 quarter hours each term, any student who finishes a term in good standing is considered to have made satisfactory progress. If a student withdraws from a course before the final date for withdrawal, no grade is given in that course. The time spent in school counts, however, and the student may be considered to have not made satisfactory progress in the event of such withdrawal.

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

Access to Student Records

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

1. The registrar of the Institute is responsible for maintaining all educational records, except for those involving Financial Aid. Caltech permits disclosure of educational records, without consent of the student, to Institute officials with legitimate educational interests in them. An Institute official is a person employed by the Institute in an administrative, supervisory, academic or research, or support-staff position (including security personnel and health and diversity center staff), a person or company with whom the Institute has contracted (such as an attorney, auditor, consultants, contractors, or collection agent), a person serving on the

Board of Trustees, or a student serving on an official com mittee, 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 inter est if he or she needs to review an education record in order to fulfill his or her professional responsibility. They are available to the registrar, provost, president, general counsel, vice president for student affairs, dean of graduate studies, dean of students, director of financial aid, and faculty of the Institute and to their respective staffs for the normal acade mic and business purposes of the Institute. Records involving financial aid are maintained by the director of financial aid, and are available to the director and staff, to the dean of graduate studies and staff, to the Faculty Committee on Scholarships and Financial Aid, and to the Faculty Committee on Graduate Study, for the purpose of granting and administering the Institute's Financial Aid program. Except as authorized by federal or state law or regulation, none of these educational records nor any personally identifiable information contained therein, other than directory information (see below), will be made available to anyone else, other than the student, without the written consent of that student. Where consent is required and given, the student, upon request, will receive a copy of the records to be released. The Institute will keep a record, available to the student and kept with his or her file, of all persons and organizations, other than those authorized within the Institute, requesting or obtaining access to the files, except when records have been produced in response to a grand-jury sub poena or other subpoena issued for a law-enforcement purpose and the court or issuing agency has ordered that the existence or the contents of the subpoena or the information furnished in response to the subpoena not be disclosed.

2. Students are allowed access to their educational records as follows: A student may inspect his or her academic tran script during normal working hours. To see other records, the student must provide a written request to the registrar or to the director of financial aid or to the dean of graduate studies or to the dean of students, or their deputies, as appropriate. A mutually convenient time will be arranged within 10 working days after receipt of the request for the student to examine the records in his or her file. At that time the student may examine all educational records in the file with the exception of those specifically exempted by Part 99 of Title 34 of the Code of Federal Regulations. The student may obtain copies of any of the records available to him or her; the cost will be 44 cents for the first page copied and 12 cents for each additional page. All reasonable requests for explanations or interpretations of the educational records

will be honored, and if inaccurate, misleading, or otherwise inappropriate data are found in these records, they will be promptly corrected or deleted. The student also has the right to insert into the records a written explanation respecting the contents of such records. If the student and the registrar, or the director of financial aid, or the dean of graduate studies, or the dean of students, or their deputies, do not agree on any item contained in the educational records, the student may submit a written request to the provost for a hearing to challenge the content of the records. The provost will schedule such a hearing within 30 days 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 hearing will be before a board composed of the provost, the vice president for student affairs, or their designated alternates, and at least one disinterested member of the faculty, who shall be appointed by the chair of the Faculty Board. None of those hearing the challenge may have a direct interest in the outcome. 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 board on the correctness of the educational record, as determined by majority vote, will be in writing, will be rendered within 10 days 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 in the files is inaccurate, misleading, or otherwise in violation of the privacy or other rights of the student, the Institute shall amend the records accordingly and so inform the student in writing. However, if, as a result of the hearing, the Institute decides that the information is not inaccurate, misleading, or otherwise in violation of the privacy or other rights of a student, it shall inform the student of the right to place in the educational records a statement commenting on the information in the records and/or setting forth any reasons for disagreeing with the decision of the Institute.

3. The Institute considers the following to be directory information: a student's name, UID, address, e-mail address, telephone listing, ID photograph, date and place of birth, major field of study, year in school, current enrollment status, expected date of graduation, 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, home town, and most recently attended educational agency or institution. Directory information may be made available to requestors at the Institute's discretion.

Any student may, however, have part or all of this information withheld by notifying the registrar in writing no later than 30 days after the commencement of classes in the academic year. That information will then be withheld for the balance of that academic year. If the information is to be withheld in subsequent years, new requests must be filed.

4. A student will not be required to waive any rights regarding access to educational records. However, a student may voluntarily waive right of access to confidential statements made by third parties respecting admission to educational agencies or institutions, applications for employment, or the receipt of an honor or honorary recognition. In case of waiver, the confidential statements will be used solely for the purposes for which they were specifically intended, and the student will, upon request, be notified of the names of all persons making such confidential statements. If a student should desire to so waive right of access, so as to facilitate the obtaining of a confidential statement of this nature, he or she should contact the registrar for the necessary form.
5. The Institute reserves the right to destroy from time to time any and all educational records that it maintains on a student, except to the extent that the law requires their maintenance for a longer period of time. However, where access to records has been requested, no destruction of those records will be allowed to take place until such access has been granted or denied.
6. Students who believe their rights under FERPA may have been violated may file a complaint with the Family Policy Compliance Office, U.S. Department of Education, 400 Maryland Avenue SW, Washington D.C. 20202-4605.

Transcripts of Records

A student, or former student, may request that official transcripts of his or her records be forwarded to designated institutions or individuals. Requests should be filed at the Registrar's Office at least five days before the date on which the transcripts are to be mailed. (See "Unpaid Bills," page 150, for complete details.)

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

The documents describing these accreditations and authorizations are on file and may be inspected in the Office of the Registrar, the Undergraduate Admissions Office, or the Office of the Dean of Graduate Studies.

Student Grievance Procedure

Caltech provides a variety of routes, most of them informal, by which students may bring complaints to consideration and resolution. In academic matters, for example, they may begin with faculty-student conversations and may extend to the deans, the division chairs, the registrar, or to various committees having faculty and student members. Undergraduate housing matters are dealt with by house officers, the resident associates, the IHC, and the assistant vice president for campus life. The dean of graduate studies is often of assistance in resolving graduate student matters. As the Institute officers responsible for the supervision of many Student Affairs offices, the assistant vice presidents for student affairs may be the appropriate persons to appeal to in case of unresolved complaints involving those offices. The Graduate Student Council and ASCIT may become involved in important complaints, and sometimes ad hoc groups are formed to make recommendations.

The grievance procedure 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, and which do not fall within the jurisdiction of the Honor System.

The first step in this procedure is to consult with the person appointed by the president of the Institute as mediator for student grievances. The mediator will assist the student in trying to work out the problem in an informal way. If the student is not satisfied with the results, he or she may appeal the case to the Student Grievance Committee. The members of the committee are undergraduates appointed by the ASCIT Board of Directors, graduate students appointed by the Graduate Student Council, faculty appointed by the faculty chair, and administrative staff appointed by the vice president for student affairs. Two members and two alternates are appointed from each of the four categories. The chair of the committee is appointed by the president and does not vote except in case of a tie. The grievant may present the case to the committee, present documents in support of the case, request that witnesses be called, and be assisted by another member of the Caltech community who is not an attorney. The committee will present its conclusions and recommendations to the president of the Institute, and the president's decision will be final. A complete statement of the student grievance procedure is available from the following offices: Student Affairs, Dean of Students, Dean of Graduate Studies, and Diversity Center.

Student Patent and Computer Software Agreement

The California Institute of Technology has the responsibility to see that inventions made and computer software developed at the Institute be used for the public benefit, be administered in such a way as to avoid cause for criticism of the Institute, and meet the Institute's contractual obligations to others.

Students at Caltech have many opportunities to work in laboratories, in shops, or with computers, sometimes on individual projects and sometimes as part of a group activity. It is not unusual under these circumstances for inventions to be made, or computer software to be written, and it is important that the student's rights in patents on such inventions and computer software be protected. The Institute's policy is to reserve to itself rights in inventions and computer software generated by faculty and staff members with the use of Institute facilities or in the normal course of their Institute duties. The student's position is different, however, and students retain all rights except in inventions or computer software generated under circumstances such that rights clearly belong to the Institute or to the sponsor of the research. In order to clarify this situation and to protect the rights of both the student and the Institute, each student at Caltech is asked to sign the following agreement.

In view of the patent and copyright policies of the Institute in force at this date and as may from time to time be amended, and as consideration for my use of Institute facilities and equipment, I hereby agree as follows.

1. The Institute agrees that I shall retain all rights in inventions and computer software generated by me at the Institute except when such inventions are first conceived or actually reduced to practice, or such computer software is written: A) in the course of the performance of work as a paid employee of the Institute; B) in the course of independent student research financed by or otherwise obligated to an outside grant to or contract with the Institute, or financed by a grant from the Institute; or C) during work in the research program of an academic staff member.
2. When I generate inventions or computer software at the Institute in connection with in the educational program of the Institute (e.g., course work, homework, theses), the Institute agrees that I shall retain rights but the Institute shall obtain an irrevocable royalty-free nonexclusive license, with the right to grant sublicenses, for any purpose whatsoever.

3. I agree to notify the Institute promptly of any discovery, innovation, or invention that is first conceived or first actually reduced to practice, or computer software written, under the conditions of paragraphs 1A through 1C above.
4. I agree to assign, and hereby do assign, to the Institute all such inventions and computer software made or written under the conditions of paragraphs 1A through 1C above, and all inventions, copyrights, patent applications, and patents relating thereto; and to execute all papers required to apply for, obtain, maintain, issue, and enforce such copy right registrations, patents, and applications; and to provide reasonable assistance regarding such copyrights, patents and patent applications, including testifying in any interference proceeding or litigation relating thereto. Expenses for the copyrights and patent applications, and for the assistance set forth in the preceding sentence, shall be borne entirely by the Institute.
5. I understand that if the Institute receives funds from the licensing of computer software or patents assigned to it by me pursuant to this agreement, in excess of unreimbursed expenses associated with obtaining, maintaining, and enforcing such copyrights and patents, I shall share in these funds according to the established Institute 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.
6. I understand that the Institute relies on the foregoing agreement when it enters into contracts with others and obligates itself with respect to inventions or computer software made or written in the course of research conducted at the Institute.
7. I also understand that this agreement does not apply to any invention that qualifies fully under the provisions of Section 2870, Chapter 2 of Division 3 of the Labor Code of the State of California, which states as follows.

   (a) Any provision in an employment agreement which provides that an employee shall assign, or offer to assign, any of his or her rights in an invention to his or her employer shall not apply to an invention that the employee developed entirely on his or her own time without using the employer's equipment, supplies, facilities, or trade secret information except for those inventions that either: (1) Related at the time of conception or reduction to practice of the invention to the employer's business, or actual or demonstrably anticipated research or development of the employer; or (2) Result from work performed by the employee for the employer. (b) To the extent a provision in an employment agreement purports to require an employee to assign an invention otherwise excluded

from being required to be assigned under subdivision (a), the provision is against the public policy of this state and is unenforceable.

Student Retention and Persistence Rates

Most undergraduates enter Caltech at the freshman level. Of the 231 freshmen enrolled during the 2007–08 academic year, 223 reenrolled in the first term of the 2008–09 academic year and are progressing, yielding a persistence rate of 97 percent. Of the 252 freshmen enrolled during the 2002–03 academic year, 223 graduated by June 2008, yielding a graduation rate for this group of 88 percent.

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 2007–08 academic year, 223 reenrolled in the first term of the 2008–09 academic year and are making satisfactory academic progress, resulting in a persistence rate of 97 percent. Of the 54 entering graduate students enrolled in M.S. programs during the 2007–08 academic year, 8 completed requirements within one year; an additional 44 reenrolled in the first term of the 2008–09 academic year and are making satisfactory progress toward a higher degree.

INSTITUTE POLICIES

Acceptable Use of Electronic Information Resources

Caltech provides electronic information resources (including, but not limited to, computers, computer accounts and services, networks, software, electronic mail services, electronic information sources, video and voice services, servers, web pages, and related services) to assist members of the Institute community in the pursuit of education and research. This policy, in conjunction with other applicable Caltech policies, sets forth the acceptable use of all Caltech electronic information resources owned or managed by Caltech, and describes the rights and responsibilities of the Institute and of faculty, staff, students, and other members of the Institute community with respect to use of these resources.

Electronic information resources are intended to be used to carry out the legitimate business of the Institute, although some incidental personal use is permitted. Faculty, staff, students, and other members of the Institute community (“users”) who use campus electronic information resources should be guided by the Institute’s Honor System, which prohibits any member of the Institute community from taking unfair advantage of any other. In addition, users who use the Institute’s electronic information resources assume responsibility for their appropriate use and agree to comply with all relevant Institute policies and all applicable local, state, and federal laws.

Users of Institute electronic information resources may not use these resources for inappropriate or unauthorized purposes. Some examples of inappropriate use are sending a communication or using electronic information resources, including web pages, that discriminate against or illegally harass, defame, offend, or threaten individuals or organizations, or to engage in other illegal conduct or conduct that violates Institute policy; destruction of or damage to equipment, software, or data belonging to others; disruption or unauthorized monitoring of electronic communications; interference with use of Institute systems; violations of computer security systems; unauthorized use of accounts, access codes, or identification numbers; use of facilities in ways that intentionally impede the legitimate computing activities of others; use of facilities for commercial purposes; use for political or lobbying activities that jeopardize the Institute's tax exempt status and, therefore, violate Institute policy; violation of copyrights, software license agreements, patent protections and authorizations, or protections on proprietary or confidential information; unauthorized use of Caltech's trademarks; violating copyright laws by downloading and sharing files; violations of privacy; academic dishonesty; sending chain mail; spamming; 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.

Password capabilities and other safeguards are provided to members of the Caltech community in order to safeguard electronic messages, data, files, and other records (including computer files and records, electronic mail, and voice mail) from unauthorized use. In addition, the Institute will routinely follow up on systems and/or accounts that appear to be compromised or are in the process of being compromised. However, these safeguards are not intended to provide confidentiality from the Institute with respect to personal messages or files stored on Institute systems. Electronic information resources are Institute property. Users should not have an expectation of privacy with respect to their use of Institute electronic information resources or data, files, or other records generated, stored, or maintained on Institute resources.

The Institute may routinely examine network transmission patterns such as source/destination, address/port, flags, packet size, packet rate, and other indicia of traffic on the servers. While the Institute will not, as a routine matter, review the content of electronic messages or other data, files, or records generated, stored, or maintained on Institute electronic information systems, the Institute retains the right, within its discretion, to inspect, review, or retain the content of electronic messages and other data, files, or records generated, stored, or maintained by users at any time without prior notification, for legitimate Institute reasons. These legitimate reasons include, but are not limited to, responding to lawful subpoenas or court orders, investigating misconduct and determining compliance with Institute policies, and locating electronic messages, data, files, or other records. Users should also understand that electronic messages, data, files, and other records generated, stored, or maintained on Institute electronic information systems may be electronically accessed, reconstructed, or retrieved even after they have been deleted. Institute access to the content of electronic mail, data, files, or other records generated, stored, or maintained by any member of the Caltech community may only be requested 1) by the provost for faculty; 2) by the associate vice president for human resources for employees; and 3) by the vice president for student affairs for students. In all cases, Institute access requires prior consultation with the Office of the General Counsel.

The use of Institute electronic information resources is a privilege, not a right, and the Institute may revoke this privilege, or decline to extend this privilege, at any time. Inappropriate use of Institute resources may result in administrative discipline up to and including separation from the Institute. Suspected illegal acts involving Institute electronic information services may be reported to state and federal authorities, and may result in prosecution by those authorities. Any questions concerning the appropriate use of any of the Institute's electronic information resources or relevant Institute policies should be directed to the provost, the chief information officer, the associate vice president for human resources, the dean of students, or the dean of graduate studies.

Accommodations for Disabilities

It is the policy and practice of Caltech to comply fully with the Americans with Disabilities Act (ADA), the Rehabilitation Act (Section 504), and other applicable federal, state, and local laws to ensure equal opportunity for qualified persons with disabilities. Caltech is committed to ensuring that there is no unlawful discrimination in any of its programs, services, activities, and terms and conditions of employment. As required by law, Caltech will provide reasonable accommodations to qualified individuals with disabilities including students, employees, and job applicants.

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

The following individuals have been designated as contacts regarding disability issues. For students, Barbara Green, associate dean of students, (626) 395-6351. For staff, April White Castañeda, senior director of employee relations, (626) 395-8167. For faculty, Jean Grinols, administrator, Provost's Office, (626) 395-6129.

Alcohol Use at Student Events

I. Basic Principles

Caltech is committed to providing its students, faculty, and staff with an environment that promotes safe and responsible social interaction.

The Institute's concern over the illicit use and the abuse of alcohol and drugs results from the serious health hazards caused by substance abuse and from the potential legal penalties for those convicted of unlawful use, possession, or distribution of these substances, and by the ways in which alcohol and drugs adversely affect the campus environment. All members of the Caltech community should be familiar with and adhere to the Institute's policy on substance abuse. Please refer to http://cit.hr.caltech.edu/policies/policies-main.html for the complete text of the policy.

Caltech's primary approach to preventing substance abuse is to educate its students regarding the medical and psychological hazards of abuse and to increase student sensitivity to the ways in which substance abuse interferes with the rights and privileges of others. The Institute encourages the future growth of a community where substance abuse is not condoned and where those with related abuse problems are provided with assistance.

The Caltech community, guided by the Honor Code, is founded on trust, respect, and responsibility. These principles apply to all aspects of Caltech life, including alcohol and substance use and abuse. Caltech has a long-standing tradition of students acting responsibly and refraining from actions that are damaging to others or to the Institute. Individuals are expected to take responsibility for their own conduct and to comply with state and federal laws as well as with Institute policy and the Honor Code.

II. Caltech Policy on Controlled Substances and Alcohol

The Institute maintains a drug-free workplace and campus. The use, possession, cultivation, manufacture, sale, or transfer of illegal drugs is prohibited. The illegal use of other drugs or prescriptions is also prohibited. Members of the Caltech community are expected to act lawfully with respect to the possession and consumption of alcoholic beverages. Possession and consumption of alcohol by individuals under 21 is prohibited. It is a violation of Caltech's policy to serve, share, or pass alcohol to anyone under 21. Anyone who is intoxicated, regardless of age, may not be served. All members of the Caltech community, including students, are prohibited from returning to work in an experimental lab after having consumed alcohol. Consumption of alcoholic beverages in public areas outside residences, such as walkways, building steps and porches, and green spaces (e.g., the Olive Walk, the Millikan Pond area, the Court of Man), is not permitted regardless of the drinker's age unless the event is registered.

Planning Student Events at Caltech

Caltech recognizes that student parties and activities are an important part of campus life. The information provided here is intended to help minimize the risks associated with sponsoring a party, and to help individuals and organizations plan and execute a safe, healthy, fun, and problem-free event.

Event planners are encouraged to consult with the assistant vice president for campus life, the dean or associate dean of students, or the dean or associate dean of graduate studies prior to the party so that the respective office can work with planners in arranging their event.

Planning Requirements

These requirements apply to events taking place in an Institute common area (any area outside of an individual's apartment or private room). Examples of common areas include house lounges, dining rooms, and courtyards, the Catalina recreation room, Dabney Lounge, etc. These planning requirements do not apply to activities that take place in private rooms within student residences or student apartments. Such locales are governed by applicable laws and conditions of the housing contract.

All student events at which alcohol will be served (including official campus functions, registered events, and private parties) must adhere to the following guidelines:

- In order to use Institute funds (including house dues, club funding, and student government funding) for an event where alcohol is served, prior authorization must be received from the assistant vice president for campus life, the dean or associate dean of students, or the dean or associate dean of graduate studies.
- Events where alcohol is served may be open only to members of the Caltech community and their invited personal guests.
- Events should not promote the inappropriate or excessive use of alcohol.
- One student must fill out the event registration form as the event host on behalf of the sponsoring organization, signifying that the organization agrees to abide by Caltech procedures and applicable law.
- Professional bartenders are required at any event where alcohol is served and participants under the legal drinking age are present. Professional bartenders may also be required at the discretion of the Institute if circumstances so require. A current driver's license with a picture, a state-issued identification card, or a passport is the acceptable means of age verification.
- A bartender may not serve alcohol to any individual who is under 21 years of age or to anyone who is intoxicated. A bartender may not serve more than one drink to one person at any one time.

- Alcoholic and nonalcoholic beverages must be free and provided in quantities determined by the proportion of guests above and below the legal drinking age. An adequate supply of quality nonalcoholic beverages must be provided throughout the duration of the party. Alcohol may not be served if nonalcoholic beverages run out. Food must also be available throughout the duration of the event.
- Campus security must be present at any registered event where alcohol is served unless the assistant vice president for campus life, the dean or associate dean of students, or the dean or associate dean of graduate studies grants an exception.
- All events must conclude by the time governed by Institute policy, which is 2:00 a.m. The bar must be closed at 2:00 a.m., and security will be present to assist in the process. This may include removing remaining alcohol to a designated secure location.
- An accessible shared supply of alcohol may not be held by houses, individuals, or clubs. This includes, but is not limited to, unregistered kegs, trash-can punches, and beer fridges.
- Any drinking game or any other activity that promotes the rapid and/or excessive consumption of alcoholic beverages is not permitted.

To determine whether your event must be registered, access the undergraduate event registration form or the graduate registration form on the Student Affairs website.

Federal and State Law

Caltech abides by federal and state laws in regard to the use of illegal drugs and alcohol. It is a criminal offense

- To use, possess, cultivate, manufacture, sell, or transfer illegal drugs, or to illegally use other drugs or prescriptions
- For any person under the age of 21 to consume, purchase, or possess alcohol
- To provide any alcoholic beverage to a person under the age of 21
- To provide any alcoholic beverage to an obviously intoxicated person
- To be under the influence of alcohol in a public place and unable to exercise care for one's own safety or that of others
- To operate equipment or vehicles after consuming alcohol or drugs
- To have in one's possession or to use false evidence of age and identity to purchase alcohol

A student's eligibility for federal financial aid may be suspended if the student is convicted, under federal or state law, of an offense involving the possession or sale of illegal drugs.

Liability
While the law regarding civil liability is complex, it is important to know that under some circumstances student houses, event sponsors, bartenders, or others might be held legally liable for the consequences of serving alcohol to underage drinkers or to obviously intoxicated persons. Persons could be sued and potentially found personally liable for damages to any injured party or parties.

Institute-Imposed Consequences for Policy Violation
Caltech will impose sanctions on individuals and organizations that violate this policy. These sanctions and penalties will depend on the severity of the offense. The penalties can be imposed by the dean or associate dean of students, dean of graduate studies, assistant vice president for campus life, the Conduct Review Committee, the Board of Control, the Graduate Review Board, and the vice president for student affairs. For undergraduate violations, the Routing Committee (made up of the chair of the Board of Control, the student cochair of the Conduct Review Committee, assistant vice president for campus life, and the dean of students) determines who will hear the case. For graduate students, the dean of graduate studies and the chair of the Graduate Review Board will meet to determine who has jurisdiction over the case. Penalties can include expulsion from the Institute and referral to civil authorities for prosecution for violations of the law. A student who is found to be selling or providing illegal drugs can be suspended or expelled from the Institute, even for a first offense.

In addition to suspension or expulsion, other sanctions may include the following:

- Verbal and written warnings
- Organizing an educational program for peers
- Community service
- The completion of an appropriate rehabilitation program
- Social probation for an individual or a group
- Persona non grata status
- Suspension from housing
- Attending a substance-abuse awareness program

Houses and student organizations that flagrantly or frequently violate the policy will have restrictions placed on parties, events, and/or other social activities. An event may be closed immediately, or other interventions may be taken to correct the violation. Disciplinary action may be invoked entirely apart from any civil or criminal penalties that the student might incur.

Students should understand that inebriation is never an excuse for misconduct—that a student's careless or willful reduction, through the use of alcohol or other intoxicants, of his or her own ability to think clearly, exercise good judgment, and respond to rational intervention may invoke more stringent penalties than otherwise might be levied.

Recent legislation allows institutions of higher education to contact parents when their adult children violate a school's alcohol or drug policy. If it is a possibility that students' behavior with respect to alcohol and drugs presents a danger to themselves and/or others, Caltech may inform parents. Such a determination will be made by the deans or the assistant vice president for campus life, in consultation with other offices as necessary.

III. Alcohol Safety

When planning an event where alcohol will be served, it is important to be aware of the need to implement a plan to promote the health and safety of your guests. Caltech's alcohol policy and programs are intended to encourage its community members to make responsible decisions about the use of alcoholic beverages, and to promote safe, legal, and healthy patterns of social interaction.

As an event host or as a participant, it is important to be educated regarding signs of intoxication, signs and symptoms of alcohol poisoning, and managing high-risk guests.

In order to manage high-risk guests, the following is a list of suggested Dos and Don'ts:

Do

Be friendly but firm
Be assertive and nonjudgmental
Make sure you have others close by for support
Use the guest's friends as your allies
Offer guests an alternative to drinking; this will allow the guest to "save face" and feel in control
Be aware of possible aggression; try to get the person away from the crowd and distracted from possible sources of anger

Don't

Be angry or obnoxious
Back down or change your mind
Hesitate to call your RA or Security
Take statements personally or get into a shouting match
Touch anyone without good reason; if someone attacks you, only use enough force to restrain them
Embarrass the guest; others observing the situation may feel a need to intervene or retaliate

In addition, the ability to differentiate between the symptoms of alcohol intoxication and an alcohol emergency is critical. Signs of intoxication include

- Talking loudly, then very softly
- Rambling or irrational speech
- Acting aggressively or belligerently

- Spilling drinks
- A decrease in coordination, e.g., missing the mouth while attempting to drink

In contrast, the signs and symptoms of alcohol poisoning are more severe and dangerous. There is no way to sober someone up quickly. It takes about as many hours to sober up as the number of drinks consumed. If an individual exhibits

- Unconsciousness or semiconsciousness
- Slow breathing—eight breaths or less a minute
- Cold, clammy, pale, or bluish skin
- No response to sounds, pinching, prodding, or poking

it is highly possible that he or she has alcohol poisoning.

What to Do:

- Telephone ext. 5000 or 395-5000 immediately
- Stay with the person until help arrives
- Observe the person's vital signs (level of consciousness, breathing rate, color of skin)
- Prevent choking by rolling the person onto his or her side

In cases of intoxication and/or alcohol poisoning, the primary concern is for the health and safety of the persons involved. Individuals are strongly encouraged to call for medical assistance for themselves or for a friend/acquaintance who is dangerously intoxicated. **No student seeking medical treatment for an alcohol or drug-related overdose will be subject to discipline for the sole violation of using or possessing alcohol or drugs.** A staff member may follow up with the student after the incident to determine his or her health and welfare.

Counseling and Treatment

Students who believe they may have an alcohol or drug problem are strongly encouraged to seek assistance through resources available at the Institute. Students should seek aid through the Health and Counseling Center, the health educator, the deans, or the assistant vice president for campus life. Such contacts will be kept confidential, except as required by law or the immediate health, safety, or security of the individual or others.

Resources

You can always contact your RA and health advocate. Additional resources include

Security	ext. 5000
Health Center	395-6393
Counseling Center	395-8331
Health Educator	395-2961
Huntington Hospital Emergency Room	397-5111

Fire Safety

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

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

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

Firearms and Other Dangerous Materials

No one is allowed to maintain, possess, transport, or use any firearms, including BB, pellet or paintball guns, or replicas that could be mistaken for real guns, or other weapons, including martial arts weapons, hunting knives, fireworks, ammunition, explosives, dangerous chemicals, or highly flammable materials (e.g., gasoline) on Institute property, including off-campus facilities. The use or threatened use of any knife as a weapon is also prohibited.

Mural Policy

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

Missing Students

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

Nondiscrimination and Equal Employment Opportunity

Caltech is committed to equal opportunity for all persons without regard to sex, race, creed, color, religion, national origin, ancestry, age, marital status, pregnancy, gender identity, sexual orientation, status as disabled veteran, a veteran of the Vietnam era or other eligible veteran, and for otherwise qualified individuals with a disability. It is the policy of Caltech to provide a work and academic environment free of discrimination. Consistent with this policy, illegal harassment will not be tolerated at Caltech. Caltech will take all reasonable steps to eliminate it in its work and academic environment.

Caltech is an equal employment and affirmative action employer and will, whenever possible, actively recruit and include for employment members of minority groups, females, disabled veterans, veterans of the Vietnam era, other eligible veterans, and otherwise qualified persons with disabilities. Caltech will hire, transfer, 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.

The provost has been designated as the Equal Employment Coordinator for faculty, the director of employee relations for staff, the dean of students for undergraduate students, and the dean of graduate studies for graduate students. The associate dean of graduate studies has been designated as Caltech's Title IX coordinator. Inquiries concerning the interpretation and application of this policy should be referred to the appropriate designated individual. These coordinators are responsible for program administration, monitoring progress, and implementing goals and action-oriented programs relating to affirmative action. Likewise, 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. Managers' performance in regards to Caltech's affirmative action goals and objectives will be evaluated, as will be their performance on other Institute goals.

Anyone who witnesses or experiences conduct he/she believes to be in violation of this policy is urged to contact any of the above mentioned coordinators, the individuals identified in related harassment policies, or the Employee Relations office immediately. Complaints will be investigated promptly and individuals who violate this policy will be subject to disciplinary action up to and including termination or expulsion.

To achieve the goals of our affirmative action program and 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.

Sexual Assault

The California Institute of Technology will not tolerate sexual assault, whether directed at males or females. It is the policy of the Institute to provide a work and academic environment free of physical assault, including sexual assault. Rape and other types of sexual assault, whether by a stranger or by an acquaintance, are violations of the law and Caltech policy. Sexual assault includes, but is not limited to, rape, forced sodomy, forced oral copulation, rape by a foreign object, sexual battery, or threat of sexual assault. Caltech views sexual assault, in any of its forms, as a very serious matter and is committed to responding promptly to, and thoroughly investigating, sexual assault charges leveled at a member of the Caltech community. To reduce the risk of sexual assault, Caltech provides education for the campus community to increase awareness of this important issue.

I. Basic Principles

A crucial part of Caltech culture is respect for one another; no member of the Caltech community should take unfair personal advantage of another member of the community. Students, faculty, and staff who wish to file a complaint against another member of the Caltech community will have their complaints treated seriously and will be treated with dignity. The Institute recognizes that a sexual assault is more than an assault on an individual's body; it is also an attack on the individual's dignity and sense of self. Therefore, the Institute is committed to seeking input from the complainant and the respondent before making any decision to take action. There may be circumstances, depending on the seriousness of the offense, in which the Institute must take action to protect the complainant or other members of the Caltech community. The Institute will provide assistance and support for survivors of sexual assault.

II. What to Do if a Sexual Assault Has Occurred

If you have been sexually assaulted, you are encouraged to seek medical, psychological, and support services provided by campus and/or community services. If emergency response is required, please call Campus Security (x5000) or local law enforcement (744-4241).

Psychological treatment is available from the Student Counseling Center or the Staff and Faculty Consultation Center. Medical treatment is available at the Caltech Health Center, Huntington Memorial Hospital Emergency Room, a private physician, or through other community resources. You will benefit from being examined for physical injury, disease, and/or the possibility of pregnancy.

Because sexual assault may involve physical trauma and is a crime, the person assaulted is urged to seek medical treatment as soon as possible so that physical evidence can be obtained. To preserve evidence, do not bathe, douche, smoke, brush your teeth, or change your clothes. If clothes have been changed, the original clothes should be put in a paper bag (paper is best for preserving evidence) and brought to the hospital. If possible, you should bring a fresh change of clothes. In most cases, evidence can be collected only within 72 hours of the assault.

Please note that the hospital and certain health-care providers have an obligation to inform the police, and the police may conduct an interview at the hospital regarding the assault. Your consent will be requested to allow collection of evidence. You can choose whether or not to disclose information to the police or to file a civil or criminal complaint. If you desire further information concerning this procedure, please contact the Diversity Center, Staff and Faculty Consultation Center, or the Rape Hotline.

Individuals who do not wish to be interviewed by the police should seek medical assistance from a private physician or other community resources. These health-care professionals may need to fulfill legally mandated reporting requirements.

III. Community Resources

If you or someone you know has been sexually assaulted within or outside of the Caltech community, there are support and resources available.

Confidential Campus Resources

Members of the Caltech community may contact any of the offices below confidentially. Personnel in these offices will listen and offer options. Talking to any of these individuals does not constitute reporting an incident involving a member of the Caltech community to Caltech. However, these offices can provide you with support and can guide you through Institute procedures. Although they will not participate in formal Institute processes or legal action, the staff in each office is available to help the complainant and/or the respondent look at all available options; decide what plan of action feels most comfortable; craft a statement that contains all of the relevant information regarding the complaint; and make decisions about how to proceed.

Sources of support and information on campus and in the community include:

Student Counseling Center	(626) 395-8331
Staff and Faculty Consultation Center	(626) 395-8360
Diversity Center	(626) 395-3221

Other campus resources:

Student Health Center	(626) 395-6393
Dean of Students	(626) 395-6351
Dean of Graduate Studies	(626) 395-5802
Campus Life	(626) 395-6174
Associate Vice President for Human Resources	(626) 395-3230
Director of Employee Relations	(626) 395-8167
Provost	(626) 395-6336
Campus Security	(626) 395-5000
Vice President for Student Affairs	(626) 395-6100

Other community resources:

Planned Parenthood	(626) 798-0706
Victim–Witness Assistance Program	(800) 773-7574
Rape Hotline	(626) 793-3385
Pasadena Police Department	(626) 744-4241
Domestic Violence Hotline	(800) 978-3600
Huntington Memorial Hospital Emergency Department	(626) 397-5111
LA Conty Info Line for Support Servs.	(626) 350-6833

IV. Procedures for Filing Complaints

A student, faculty, or staff member who has been sexually assaulted by a member of the Caltech community is strongly encouraged to file a complaint with the Caltech administration as well as local law enforcement. If you would like support and guidance in filing a complaint, please contact the Diversity Center, the Staff and Faculty Consultation Center, Employee Relations, and/or the Security Office.

A. Filing a Complaint with Civil Authorities

Members of the Caltech community wishing to report a sexual assault to the police are encouraged to seek support and guidance from the Diversity Center, (626) 395-3221. The telephone number of the Pasadena Police is (626) 744-4241.

B. Filing a Complaint on Campus—Overview

A student, faculty, or staff member who wishes to file a campus complaint against a member of the Caltech community should do so as soon as possible after the assault, although complaints may be filed at any time. Complaints should be brought to the attention of one of the following individuals: provost, deans, director of employee relations, employee relations specialists, student affairs directors, division chairs, and division administrators, who will ensure that the complaint reaches the appropriate investigating office. If the respondent is a student, the complaint will be forwarded to the dean or associate dean of students or dean or associate dean of graduate studies; if staff, to the director of employee relations; and if faculty, to the provost. Within a reasonable length of time the person accused, the respondent, will be notified of the nature of the complaint and an investigation will begin. If administrative changes are needed to protect the rights of either party during the investigation, the appropriate administrators shall see that they are made.

The complainant should immediately notify any of the above individuals if anyone associated with the matter is under continuing threat or is being subjected to retaliation. Immediate action will be taken, and in such cases the complainant has the right to file another complaint.

C. Campus Complaint Procedure

Initial Meeting

The administrator receiving the complaint will

- Ask the complainant questions to assess whether there is a continuing threat to the complainant and/or other members of the community.
- Ensure that the complainant is given appropriate protection, including protection from retaliation for the com plaint. Such protection may include restrictions on the accused.
- Provide a copy of this policy to the complainant.
- Review available resources, including medical and psychological counseling.
- Request a written statement from the complainant. Review confidential campus resources that could assist the complainant in the process.

As soon as practicable after a complaint is received, the Dean of Students office or the Dean of Graduate Studies office, the Provost's office, or Employee Relations will form a team to investigate the complaint. The lead investigator will be from the same area as the respondent. For example, if a staff member makes a complaint against a faculty member, a representative of the provost will lead the investigation, and if a faculty member files a complaint against a staff member, a representative of the director of employee relations will lead the investigation. The individuals involved in the investigation will respect the privacy of the complainant and that of all parties involved while they complete a thorough review of the situation. All participants will be required to keep the contents of the investigation confidential. The investigation should be completed as soon as practicable, usually within 30 days after the formation of the team. The Caltech investigation will occur independently from any legal proceedings that may take place.

The investigative process will be the following:

- The respondent should be notified as soon as possible after a complaint is filed. The respondent will receive a verbal summary of the complaint and a copy of this policy.
- The investigators will review the written statement from the complainant if one has been prepared, and interview the complainant and the respondent. Each will be allowed to have a friend who is a member of the Caltech community present during his or her interview. The friend will serve as an observer and will not participate in the proceedings.
- The complainant and the respondent will be asked to suggest available witnesses. Others may be interviewed to obtain relevant information.

Both parties will be kept informed of the status of the investigation.

Determination

The investigators will consult with Institute counsel and make a recommendation to the relevant dean, the provost, or Employee Relations, as appropriate, regarding the charges and the appropriate consequences, including disciplining of the respondent.

In addition, the investigators will prepare a summary record of the case for the president of Caltech. This record will be considered a confidential Institute document and will be provided only to the vice president for business and finance (for staff), the provost (for faculty), the vice president for student affairs (for students), and the president in the case of an appeal.

Resolution

The Dean of Students office, the Dean of Graduate Studies office, the Provost's Office, or Employee Relations, as appropriate, will inform both parties of the outcome of the investigation in writing within seven days after receiving the recommendation and completing consultation with counsel. The provost, the vice president for student affairs, or the vice president for business and finance will carry out any disciplinary consequences and should consult with Institute counsel for aid in determining the Institute's legal duties and obligations before taking appropriate disciplinary action based on the team's findings. Discipline can include, but is not limited to, the following: counseling, probation, involuntary leave of absence, expulsion and/or termination. If the complainant is found to have acted in bad faith in bringing the charges, disciplinary action may also be taken.

Appeal

Any party involved in the investigation may appeal the decision to the president of Caltech. The appeal must be on the grounds of improper procedure or an arbitrary decision based on evidence in the record. The president will appoint an investigator to interview both parties and confer with the original investigators before deciding whether to accept the original judgment or authorize further investigation or deliberations.

Confidentiality
On a need-to-know basis, the following individuals at the Institute may also be informed of the fact that a sexual assault complaint has been made and that both parties are members of the Caltech community:

President
Vice President/Assistant Vice President for Student Affairs
Campus security
Dean of Students
Dean of Graduate Studies
Assistant Vice President for Campus Life
Resident Associate
Provost
Associate Vice President for Human Resources
Director of Employee Relations
Director of the Diversity Center
Director of the Student Counseling Center
Director of the Health Services
Staff and Faculty Consultation Center
Office of Public Relations

The names of the individuals involved will not be released unless the release is essential to the health and safety of the complainant or is otherwise required in order to fulfill the legal obligations of the Institute. In such rare circumstances, the vice president for student affairs (for students), the provost (for faculty), and the associate vice president for human resources (for staff) are the only persons authorized to make an exception to the rule of complete confidentiality regarding the names of those involved. If an exception is made to this rule, the parties involved in the incident will be notified as soon as possible.

Title IX

Title IX of the Education Amendments of 1972 is a comprehensive federal law that prohibits discrimination on the basis of sex in any federally funded education program or activity. Inquiries concerning the Institute's policies, compliance with applicable laws, statutes, and regulations (such as Title IX and section 504), and complaints may be directed to Title IX coordinator, Felicia Hunt (associate dean of graduate studies), (626) 395-3132. Inquiries about the laws and compliance may also be directed to the assistant secretary for civil rights, U.S. Department of Education.

Unlawful Harassment

It is the policy of the Institute to provide a work and academic environment free of unlawful harassment and retaliation. Harassment is the creation of a hostile or intimidating environment in which verbal or physical conduct, because of its severity and/or persistence, is likely to interfere significantly with an individual's work or education, or affect adversely an individual's living conditions. Harassment in any form, based on sex, race, color, age, national origin, disability, religion, gender identity, sexual orientation, or any other characteristic protected by state or federal laws, is prohibited, as are all forms of sexual intimidation and exploitation. All faculty, students, and staff should be aware that the Institute will not tolerate any conduct that constitutes illegal harassment. The Institute also takes prompt action when notified about harassment by third parties such as nonemployees, vendors, or contractors. Complaints of harassment will be promptly and thoroughly investigated and appropriate action, including disciplinary measures, will be taken when warranted.

Faculty, students, and staff, at all levels, are responsible for maintaining an appropriate environment for study and work. This includes conducting themselves in a professional manner, actively discouraging harassment, and taking appropriate corrective action to prevent and eliminate harassment. Caltech requires that any employee who is responsible for directing other Caltech employees participate in training regarding illegal harassment, including sexual harassment, at least every two years.

Faculty, students, and staff have the right at any time to raise the issue of harassment without fear of retaliation. Caltech policy prohibits retaliation against an individual for making a good-faith report of alleged harassment. Any faculty, student, or staff who feels that he or she has been harassed should review the Procedures for Investigating and Resolving Unlawful Harassment Complaints at Caltech and immediately bring the matter to the attention of his or her supervisor or any of the individuals listed below. They will handle matters brought to their attention with sensitivity and discretion.

Deans
Director of employee relations
Division administrators
Division chairs
Employee Relations consultants
Provost
Student Affairs directors (including the master of student houses)
Director of the Diversity Center

The Institute also offers members of the Caltech community the choice of seeking confidential counseling outside the Institute's formal mechanisms for resolving 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. Those seeking this type of assistance should check with the offices listed below, each of which has its own mandate and guidelines for providing services:

Staff and Faculty Consultation Center
Student Counseling Center
Diversity Center

Information for faculty, students, and staff is also available from the Diversity Center, Staff and Faculty Consultation Center, any Student Affairs office, resident associates, or Employee Relations.

Any member of the Caltech community who believes he or she has been a witness to or a target of harassment is urged to report promptly the facts of the incident(s) to any of the above offices. Delay in reporting may impede the Institute's ability to take appropriate action. In addition, an employee who believes he or she has been harassed has the right to file a complaint with the federal Equal Employment Opportunity Commission or the California Department of Fair Employment and Housing, which have the authority to remedy violations; students may file complaints with the federal Office for Civil Rights. No member of the Caltech community will be retaliated against for making a good-faith report of alleged harassment or for participating in an investigation, proceeding, or hearing conducted by the Institute, or by a state or federal agency.

I. Guidelines Regarding Harassment

Harassment

Harassment is the creation of a hostile or intimidating environment in which verbal or physical conduct, because of its severity and/or persistence, is likely to interfere significantly with an individual's work or education, or affect adversely an individual's living conditions. Abusive or harassing behavior, verbal or physical, which demeans, intimidates, threatens, or injures another because of his or her personal characteristics or beliefs, is subject to the Institute's disciplinary process. Examples of personal characteristics or beliefs include race, ethnicity, national origin, religion, disability, age, gender identity, and sexual orientation. Some kinds of behavior that are clearly intended to harass, while inappropriate and not tolerated at Caltech, may not be illegal because the behaviors are not clearly linked to these personal characteristics or beliefs. These types of behavior may be dealt with through the student disciplinary process or through supervisory intervention, including the Caltech progressive disciplinary process.

Harassment must be distinguished from behavior which, even though unpleasant or disconcerting, is appropriate to the carrying out of certain instructional, advisory, or supervisory responsibilities or is objectively reasonable under the circumstances. Similarly, instructional responsibilities require appropriate latitude for pedagogical decisions concerning the topics discussed and the methods used to draw students into discussion and full participation. There are, however, obligations of civility and respect for others that underlie rational discourse. Behavior evidently intended to dishonor such characteristics as race, gender 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 violative of law and Institute policy. Some examples of incidents that may constitute illegal harassment follow.

- An adviser tells a minority 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.
- An older employee is disciplined for insubordination when the same conduct is tolerated from younger employees.
- Swastikas have been painted on the door of a room often used to prepare for the observance of the Jewish Sabbath.
- A student tells a racially offensive joke within a study group session with other students.
- Downloading or viewing pornography that is seen by others.

Of course, in order to make an accurate judgment as to whether these incidents are illegal or violate policy, the full context in which these actions were taken or statements made must be considered. Conduct of this type, therefore, will initiate an investigation, since making tolerance of illegal harassment or submission to it a condition of employment, evaluation, compensation, or advancement is a serious offense.

Sexual Harassment

Sexual harassment is unlawful, violating Title VII of the Civil Rights Act of 1964, as amended, Title IX of the Education Code, and California state law. Sexual harassment is defined as follows: Unwelcome sexual advances, requests for sexual favors, and other verbal or physical conduct of a sexual nature constitute sexual harassment when

(1) submission to such conduct is made either explicitly or implicitly a term or condition of an individual's employment or education,

(2) submission to or rejection of such conduct by an individual is used as the basis for decisions affecting that individual, or

(3) such conduct has the purpose or effect of unreasonably interfering with an individual's performance or creating an intimidating, hostile, or offensive environment.

The test is not whether the person participated voluntarily; the test is whether the conduct was unwelcome.

Sexual harassment by peers, coworkers, or third parties such as nonemployees, vendors, or contractors is a form of prohibited sex discrimination where the objectionable conduct creates a hostile educational or work environment. Both males and females are protected from peer sexual harassment. Moreover, sexual harassment is prohibited regardless of the sex of the harasser, e.g., even where the harasser and the person being harassed are members of the same sex.

Some examples of conduct that may constitute harassment are

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

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

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

When a consensual personal relationship arises and a power differential exists, consent will not be considered a defense in a claim that the Institute's unlawful harassment policy has been violated. The individual in the relationship with greater power will bear the burden of accountability.

Investigations
The Institute is firmly committed to resolving allegations of harassment fairly and quickly. To ensure that open and forthright dialog occurs, attorneys are not permitted to accompany individuals during interviews, nor are interview sessions recorded in any manner. Those interviewed are always entitled to submit a written statement if they so choose or to consult with others regarding the interview, keeping in mind that these proceedings must be kept as confidential as possible.

II. Procedures for Investigating and Resolving Unlawful Harassment Complaints at Caltech

Basic Principles
The Institute is committed to maintaining a work and academic environment for all members of the Caltech community that is free of unlawful harassment, including sexual harassment. A crucial part of Caltech culture is respect for one another; no member of the Caltech community should take unfair personal advantage of another member of the community.

Caltech also is dedicated to the free exchange of ideas and to intellectual development as part of the campus milieu. Harassment, as defined by the Institute's policy on unlawful harassment, is neither legal nor a proper exercise of academic freedom. This policy is not intended to stifle vigorous discussion, debate, or freedom of expression generally, or to limit teaching methods. Harassment compromises the tradition of intellectual freedom and the trust placed in the members of the Caltech community.

Caltech provides resources that address unlawful harassment and sexual harassment. Law and Caltech policy also prohibit retaliation against an individual for reporting any type of harassment.

Copies of the Institute's nondiscrimination, unlawful harassment, and other policies are available from Human Resources, any Student Affairs office, Dean's offices, the Diversity Center, the Staff and Faculty Consultation Center, and the Provost's Office. Policies are also published in the *Caltech Catalog* and the *Employee Handbook*, and are on the Caltech website. The policies and these procedures identify appropriate people on campus to contact with complaints.

Procedures
A member of the Caltech community who believes he or she has been subjected to harassment, including sexual harassment, should review the Institute's policy. There are several courses of action available to address the problem, each with different consequences and implications with respect to confidentiality and resultant

action. These options are not mutually exclusive. The complainant may choose which course to follow and may submit a formal complaint at any time.

A. Informal Options

An individual who believes that he or she has been harassed may choose to resolve his or her concerns informally. In general, the goal of the informal options is to quickly end offending behavior without utilizing disciplinary action. Third parties 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. Complainants should consider at the outset whether such changes might be desirable. Informal options include

1. Talking personally with the offending individual, or writing a letter asking him or her to stop. This is a personal step taken solely among the relevant parties.
2. Speaking to members of the Student Counseling Center, the Staff and Faculty Consultation Center, or the Diversity Center. Such conversations are confidential and are not communicated to individuals within or outside the Institute.
3. Resolving the complaint informally with the help of a third party who does not have a faculty, supervisory, or managerial position at Caltech. This could be a peer for staff; or, for students, a peer, a resident associate, or a member of the Board of Control or the Graduate Review Board. The goal here is to allow the parties to resolve complaints without an investigation and without elevating the complaint within the Institute. The person here is not obligated to share this information with other persons holding positions of responsibility at Caltech.
4. 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 the Institute. However, a person in these official positions is obligated to follow up to be sure the situation has been resolved. This action might include referring to an appropriate individual within the Institute or sharing some of this information with other persons holding positions of responsibility at Caltech.

B. Formal Complaints

A formal complaint is a request that the Institute take action. The complainant may file a formal complaint by reporting the offending conduct to individuals holding any of the following positions: provost, dean, director of employee relations, employee relations consultant, student affairs director (including master of student houses), division chair, or division administrator. The complaint is then taken to the provost, director of employee relations, or dean(s) as appropriate (for faculty, postdoctoral scholars and staff, and students, respectively). This individual initiates an investigation described more fully below.

Protection of complainant. Because the Institute encourages staff, faculty, and students to report and address incidents of harassment, complainants will be protected: retaliation against any member of the Caltech community is strictly prohibited. Overt or covert acts of reprisal, interference, discrimination, intimidation, or harassment against an individual or group for exercising his or her rights under this policy will be subject to appropriate and prompt disciplinary or remedial action.

Administrative and/or academic changes may be needed in order to protect the rights of the complainant. These changes should be discussed with the appropriate parties: provost, director of employee relations, or dean(s). Changes might include transfer of supervisory or evaluative responsibility regarding grading, supervision, tenure review, letters of recommendation, etc. Care will be taken to protect both the complainant and the respondent with the greatest degree of confidentiality. A complainant may have an adviser or support person present when reporting harassment. However, the proceeding is an internal Caltech function and, therefore, the presence of legal counsel is not permitted by anyone during the conduct of these procedures.

C. Details of Formal Complaints

- Formal complaints of harassment can be made orally or in writing, but if made orally, should, in the end, be put in writing.
- Complaints should be brought to the attention of one of the following individuals: provost, dean, director of employee relations, employee relations consultant, student affairs director, division chair, or division administrator. They will ensure that complaints reach the provost, director of employee relations, or the dean(s), as appropriate.
- Within a reasonable length of time the accused party (“the respondent”) will be notified of the nature of the complaint, and an investigation will begin. If administrative changes are needed to protect the rights of the complainant during the investigation, the appropriate administrators shall see that they are made.
- All formal complaints will be investigated within a reason able length of time after the complaint has been made, normally within 120 days. An individual, a committee, or an outside consultant may conduct the investigation. The purpose of the investigation is to determine the facts relating to the complaint.

- Each individual or team member who conducts an investigation will be trained in various aspects of harassment. Because of the sensitive nature of these investigations, he or she will consult with the general counsel for legal assistance in investigative techniques, in applying legal standards regarding harassment, and in determining the Institute's legal duties and obligations.
- The complainant and respondent will be informed of the relevant procedures and will have an opportunity to comment on the suitability of the investigator(s).
- The Institute's nondiscrimination and equal employment opportunity (EEO) and harassment policies, and the Institute's policy against retaliation will be reviewed with both parties. The complainant and respondent shall be given the opportunity to present their cases separately to the investigator(s) and to suggest others who might be interviewed. Subsequently the investigator(s) can, if appropriate, interview other parties to reach findings and conclusions.
- All parties who participate in investigative interviews may submit written statements. Investigatory meetings will not be recorded.
- The investigator(s) will summarize for the respondent the evidence in support of the complaint to allow the respondent the opportunity to reply. The investigation will remain confidential to the extent possible.
- Findings and conclusions in the case will be reported to the respondent's manager, dean, or the provost, as appropriate, within 30 days of the investigation being concluded. Additionally, the report will include recommendations regarding resolution and sanctions, as well as measures to prevent the occurrence of similar instances.
- Exceptions to or modification of these procedures can be made by the provost, the dean(s), or the director of employee relations if required for fairness or practical necessity. Exceptions must be made in writing and notice provided to both the complainant and respondent. Other administrative issues regarding the conduct of the investigation will be decided by the provost, dean(s), and director of employee relations, as needed.
- Investigative files are confidential and will be maintained in the appropriate administrator's office.

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

1. A violation of the Institute's EEO and/or harassment policies occurred.
2. Inappropriate behavior occurred, but did not constitute a violation of the Institute's policies on discrimination and/or harassment. For example, the respondent improperly used the power of his or her position, used poor judgement, or

violated applicable standards of ethical behavior.
3. The charges were not supported by the evidence.
4. The charges were brought without any basis or without a reasonable, good-faith belief that a basis existed.

D. Resolution

As soon as practicable after receiving the findings of the investigator(s), management or administration shall review the findings with the dean(s), managers, division chairs, and others as necessary. Both the complainant and respondent shall be informed of the results.

If a violation of Institute EEO and/or harassment policies occurred, sanctions shall be imposed. Depending on the severity of the case and role at Caltech, possible sanctions include, but are not limited to

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

If the respondent was not found to have violated Institute policy on harassment, but the investigation concludes that he or she violated another Institute policy, or committed some other wrongful or improper act, appropriate sanctions will be imposed. Likewise, if the complainant is found to have brought charges without any basis or without a reasonable, good-faith belief that a basis existed, appropriate sanctions will be imposed on the complainant.

E. Appeals

Appeals must be submitted in writing within 30 days of notification of the decision. Appeals by a faculty member of decisions or actions by the provost that affect academic freedom and tenure can be made to the Faculty Committee on Academic Freedom and Tenure as indicated in Chapter 4 of the *Faculty Handbook*. Other appeals for faculty and appeals by postdoctoral scholars can be made to the president.

Student appeals can be made to the vice president for student affairs or his or her designee. Staff appeals can be made to the associate vice president for human resources or his or her designee.

F. Further Complaints

The complainant should notify the provost or division chair, the dean(s), or director of employee relations immediately if the corrective action does not end the harassment, or if any retaliatory action occurs. In such cases, the complainant has the right to file another complaint.

Section Two

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 applied and computational mathematics group, the solid mechanics, impact mechanics, and deployable space structures laboratories, the hypersonics and hydrodynamics facilities, the explosion dynamics and detonation physics laboratories, and the Joe and Edwina Charyk laboratory of bioinspired design and biopropulsion, as well as the various disciplines making up the broad field known as aerospace.

Areas of Research

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

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

- *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, and 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 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, and nondestructive evaluation/structural health monitoring (NDE/SHM) of structures.
- *Space Technology.* The industrial utilization and exploration of space must address a wide range of engineering problems. Examples of research activities include lightweight structures for large aperture systems, in-space manufacturing, material and structural behavior in extreme temperature and radiation environments, spacecraft shielding against hypervelocity impact threats, the mechanics of sample containment for planetary protection, low-g biomechanics, biomimetics of locomotion in planetary atmospheres, hypersonic reentry into planetary atmospheres, in-space propulsion, guidance, navigation and control, and launch-vehicle performance and safety. Opportunities exist for research in collaboration with the Jet Propulsion Laboratory.
- *Computational Solid Mechanics.* Computational solid mechanics addresses phenomena ranging from the atomistic scale, e.g., nanoindentation, 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 subjects 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, 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, interdisciplinary methods based on developments in materials science and control techniques. Manipulation of canonical and simple model flows to probe fundamental issues of flow physics and control. Development of smart, biomimetic boundaries. Development of practical control and measurement techniques and devices. Experimental study of wall-bounded turbulence for scalability of control from the lab to large-scale applications.
- *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.

Physical Facilities

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

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

State-of-the-art electronic instrumentation is being developed and used. Extensive use is made of computer systems for real-time control of experiments, for data acquisition, processing, and storage, and for digital image processing. Computational facilities include powerful workstations, on-campus parallel processing 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 Institute. 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, biology, etc., 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 electromagnetics, and computational fluid dynamics. Through study outside of applied and computational mathematics, each student is expected to become competent in some special physical or nonmathematical field. In this way, subjects for research appear naturally, and a broad educational program is provided.

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

Areas of Research

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

APPLIED MECHANICS

Areas of Research

Advanced instruction and research leading to degrees of Master of Science and Doctor of Philosophy in applied mechanics are offered in such fields as elasticity; plasticity; wave propagation in solid media; mechanics of quasi-static and dynamic fracture; dynamics and vibrations; finite element analysis; and stability, control, and system identification of mechanical and structural systems.

Research studies in these areas that illustrate current interests include linear and nonlinear random vibrations of uncertain dynamical systems; structural dynamics and control for earthquake and wind loads; linear and nonlinear problems in static and dynamic elasticity, plasticity, and viscoelasticity; computational mechanics; mechanics of time-dependent fracture; chaotic behavior of dynamical systems; and material instabilities and phase transformations in solids.

Physical Facilities

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

APPLIED PHYSICS

An interdivisional program in applied physics for both undergraduate and graduate study was initiated in 1970. Applied physics at Caltech is in a fortunate position: The comparatively small size of Caltech coupled with its great strength in both the pure sciences and engineering make it possible to have a faculty with a wide interest in the application of modern physics to technology, without losing close interaction with “pure subjects.” At present, members of four divisions—Engineering and Applied Science; Physics, Mathematics and Astronomy; Chemistry and Chemical

Engineering; and Geological and Planetary Sciences—participate in instruction and research in applied physics leading to a B.S. degree as well as to M.S. and Ph.D. degrees.

The program is designed for students who are deeply interested in physics but at the same time are fascinated by the interrelation of physical problems and technological development; i.e., students who like to work with problems in physics that originate from or result in applications. A sharp division between "pure" and "applied" physics or between applied physics and engineering cannot be drawn, and the option of applied physics should be considered a bridge rather than a divider. A student is expected to have a thorough background in physics, as well as a broad background in related fields of technology.

Members of the faculty involved with the educational and research activities in applied physics remain members of their respective divisions. Graduate students who choose the applied physics option will do research in one of the cooperating divisions.

In setting up the undergraduate curriculum, every effort has been made to facilitate the transition into and out of the option. In general an undergraduate student in applied physics will devote somewhat more time to the study of condensed matter than will the "pure" physicist. Since it is expected that most students will be interested in experimental research, a special effort has been made to set up challenging laboratory courses and to provide an opportunity to do a senior thesis.

For first-year graduate students and adventurous seniors, a set of basic courses covering broad areas in applied physics is available, supplemented by a set of more specialized courses often closely related to a specific research effort.

Areas of Research and Physical Facilities

Research in applied physics covers a broad spectrum of activities, ranging from nanostructured materials, solid state devices, and photonics to biophysics and plasma physics. There is research in progress in single-molecule biophysics, synthetic biology, microfluidics, nanostructure fabrication and application in photonics and electronics, ultrahigh-speed fiber optic devices and communications systems, compound semiconductor materials and device physics, spin-dependent transport, photovoltaics, chemical vapor deposition processes, and fluid dynamics. The research program is centered in the Thomas J. Watson, Sr., Laboratories of Applied Physics. This 40,000-square-foot building contains research laboratories including a central micro/nano fabrication facility as well as offices, conference rooms, and a classroom, nestled around an attractive courtyard.

ASTROPHYSICS

The astronomical observatories at Palomar, the W. M. Keck Observatory, the Owens Valley Radio Observatory, the Combined Array for Research in Millimeter-wave Astronomy (CARMA), the Chajnantor Observatory, and the Caltech Submillimeter Observatory together constitute a unique and unprecedented concentration of ground-based facilities in astronomy.

Access to satellite-based infrared observations is provided by Caltech's Infrared Processing and Analysis Center (IPAC) and the Spitzer Science Center (SSC). For example, IPAC currently supports a number of NASA missions: 2MASS, an all-sky survey at 2 microns, and the Infrared Space Observatory (a mission of the European Space Agency). The SSC is conducting the science operations of the Spitzer Space Telescope—one of the great space observatories. The GALEX mission, a space UV survey of the sky, is also used by Caltech.

The Division of Physics, Mathematics and Astronomy also conducts work in theoretical astrophysics, laboratory astrophysics, gravitational-wave physics, and infrared and submillimeter astronomy, as well as studies of the cosmic microwave background (CMBR).The radio astronomy group works in close collaboration with the optical astronomers in Pasadena. There is close cooperation between these groups and the students and astronomers interested in planetary physics and space science. Caltech is also among the leaders in the development of the National Virtual Observatory.

As a result of the cooperation possible over a broad range of astronomy and theoretical astrophysics, unsurpassed opportunities exist at Caltech for advanced study and research. Courses of study depend upon a broad and thorough preparation in physics, mathematics, and other relevant subjects; the faculty offers advanced instruction in astronomy, astrophysics, solar physics, planetary physics, and astronomical instrumentation and techniques.

Areas of Research

Both observational and theoretical astrophysics are actively pursued. Topics of current interest in optical and infrared astronomy include observational cosmology; spectroscopic and spectrophotometric studies of quasars and galaxies; studies of the dynamics and composition of galaxies and clusters, nebulae, and interstellar matter; planet and star formation; statistical studies pertinent to cosmology, the structure of the galaxy; globular clusters; gamma-ray bursts; neutron stars; digital sky surveys; and many others.

Research in planetary and solar system astronomy is pursued in cooperation with groups in the Division of Geological and Planetary Sciences.

The research in radio astronomy covers cosmology, via observations of the microwave background radiation, and the physical properties of galactic and extragalactic radio sources, including quasars, pulsars, radio galaxies, stellar envelopes, and the planets. The properties of the interstellar medium in our own and other nearby galaxies are investigated in spectroscopic studies of various atomic and molecular spectral lines.

Theoretical astrophysics is pursued not only in the astrophysics department, but in physics and geology as well, and at Caltech includes work on supernovae, pulsars, stellar structure and evolution, stellar and planetary atmospheres, interstellar and intergalactic matter, the physics of radio sources, nucleosynthesis, relativity, and cosmology.

Physical Facilities

The Rockefeller Boards provided, in 1928, for the construction by the Institute of an astronomical observatory on Palomar Mountain, equipped with a 200-inch reflecting telescope, 48-inch Samuel Oschin and 18-inch Schmidt wide-angle telescopes, and other auxiliary instruments, together with an astrophysical laboratory on the Institute campus. The 48-inch Samuel Oschin Telescope has made possible complete surveys of the northern sky. It is now equipped with a major new digital camera, which will lead to a new generation of sky surveys. The Palomar telescopes have modern instrumentation and detectors designed for both optical and infrared wavelengths. The 200-inch Hale Telescope has been used to make many historical, fundamental discoveries ever since its commissioning in 1948, and through the present day. It is now also used for pioneering advances in adaptive optics.

A multipurpose solar equatorial telescope at an observing station at Big Bear Lake is now run jointly with the New Jersey Institute of Technology.

The Owens Valley Radio Observatory is in a radio-quiet location 400 km north of Pasadena, near Big Pine, California. Its facilities include a 40-meter telescope, a five-element interferometer for solar studies, and a 5.5-meter telescope dedicated to observations of polarized radio emission from the galaxy. The Combined Array for Research in Millimeter-wave Astronomy (CARMA) is a joint project between Caltech, the University of California, the University of Illinois, and the University of Maryland. It consists of 15 antennas, located in an isolated area in eastern California. The high-precision 10-meter telescopes of the millimeter array are used at wavelengths of 1.3 to 4 mm to map the distribution of interstellar gas and dust in star-forming regions of our own and other galaxies. The array also enables detailed studies of the sun, planetary atmospheres, and the envelopes around evolved stars. These telescopes, which are equipped with very sensitive cryogenically cooled receivers and sophisticated signal-processing and data-recording systems, give Caltech staff and students the widest range of observing opportunities available at any university-related radio observatory in the world.

The Caltech 10-meter Submillimeter Observatory, located on Mauna Kea, Hawaii, was completed in 1986 for the study of the chemistry and physics of planets and cool regions of the interstellar medium.

The Chajnantor Observatory is situated at an altitude of 5,080 m in the Chilean Andes. It is the site of the Cosmic Background Imager, which is used for cosmic microwave background studies, and will also be the site of the QU Imaging Experiment (QUIET) and the Clover experiment, both of which aim at very high sensitivity polarized microwave background studies.

The Keck Foundation funded the construction of two 10-meter optical-infrared telescopes, operated jointly with the University of California as part of an interferometer. Each Keck Telescope has four times the power of the Palomar 200-inch. They can be combined as an interferometer of unprecedented power. These are the two largest optical-infrared telescopes in the world, equipped with adaptive optics and state-of-the-art optical and infrared instrumentation, and they have made numerous fundamental advances in astronomy and cosmology. Caltech is also a major partner in the development of the Thirty-Meter Telescope (TMT).

BEHAVIORAL AND SOCIAL NEUROSCIENCE

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

Areas of Research

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

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

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

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

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

Areas of Research
General areas of research represented within the option include signal transduction, cell cycle, DNA and RNA structure and metabolism, control of gene transcription during development, electron transport proteins and bioenergetics, biological catalysis, macromolecular structure, membrane proteins, and biotechnology and biomolecular engineering. More specific examples of biological phenomena currently under study include the transduction of signals received by cell surface receptors into an appropriate response, as in chemotaxis or transmission of signals across synapses in the nervous system; the replication of DNA; the biochemical networks that control initiation and termination of cell division; the controlled transcription of DNA sequences in the genome into RNA and the processing of this RNA into mRNA and the subsequent translation into protein; the molecular mechanisms controlling the differentiation of precursor cells into specialized cells such as neurons, lymphocytes, and muscle cells; the mechanisms by which synaptic transmission in the brain is regulated during thinking and the formation of memories; the processes, driven by funda-

mental 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 photopigments 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

■ *Biodevices* (Burdick, Heath, Pine, Roukes, Tai, Yang)—BioNEMS, BioMEMS, laboratories-on-a-chip including microfluidic systems, neural networks, microscopes, and diagnostics, novel measurement principles, neural interfaces and prostheses.

■ *Bioimaging* (Dabiri, Fraser, Gharib, Guo, Meyerowitz, Pierce, Yang)—Biophotonics, advanced imaging technologies, computational image analysis, noninvasive biomedical imaging, single-molecule technologies, flow-field imaging technologies, in-situ amplification.

■ *Bioinspired Design* (Dabiri, Dickinson, Gharib, Murray, Tirrell)—Engineering physiological machines, fluid-structure energy conversion and harvesting, engineering self-powered technologies, control systems, synthetic heteropolymers.

■ *Biomechanics* (Asthagiri, Bhattacharya, Dabiri, Dickinson, Gharib, Guo, Phillips)—Molecular and cellular biophysics, biopropulsion, cardiovascular mechanics, muscle and membrane mechanics, physiology and mechanics of flapping flight, multicellular morphodynamics, cell-biomaterial interactions.

■ *Biomedical Engineering* (Asthagiri, Burdick, Davis, Fraser, Gharib, Heath, Pierce, Yang)—Neural prosthetics, molecular imaging during surgery, logical molecular therapeutics, BioNEMS diagnos tics, on-chip diagnostic laboratories, nanoparticle drug delivery, locomotion rehabilitation.

■ *Cell and Tissue Engineering* (Asthagiri, Fraser, Gharib, Guo, Tirrell)—Multicellular morphodynamics, principles of feedback between tissue mechanics and genetic expression, nonnatural protein biomaterials, cell-biomaterial interactions, developmental patterning.

■ *Molecular Programming* (Murray, Pierce, 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* (Arnold, Asthagiri, Elowitz, Murray, Pierce, Rothemund, 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* (Asthagiri, Doyle, Guo, Heath, Meyerowitz, Murray, Phillips, Sternberg, Elowitz, Lester)—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, molecular biology, neurobiology, and structural 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. 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 Beckman Laboratories 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 state-of-the-art microchemical facility for sequencing and synthesizing biologically important macromolecules, 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.

BIOTECHNOLOGY

Biotechnology is a growing area of interdisciplinary research with a long tradition at Caltech. It includes a wide range of research opportunities in the Divisions of Biology, Chemistry and Chemical Engineering, and Engineering and Applied Science. Areas of emphasis include the development and application of new methods and instruments for studying a spectrum of biological problems ranging from the structure, function, and chemistry of key macromolecules such as proteins and DNA to the imaging of cellular processes or the complex problems of neural systems. Other programs focus on the creation, study, and use of novel microorganisms and proteins, combining classical and molecular genetic approaches with modern chemistry and engineering science. New challenges in data analysis and molecular modeling bring together research in biology and chemistry with computer science and applied and computational mathematics. Research in these areas leading to the Ph.D. may be pursued by entry into one of the relevant graduate options in the divisions listed above. The interdisciplinary nature of biotechnology often includes course work and research collaborations that embrace more than one division. Each graduate option specifies the emphasis of the educational program and its degree requirements.

Excellent facilities for biotechnology research are available in each of the participating divisions. For example, the Beckman Institute provides extraordinary resources for development and application of new instruments and methods.

CHEMICAL ENGINEERING

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

Areas of Research

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

- *Biological Design and Engineering.* Engineering of proteins and metabolic pathways by computational and laboratory evolution approaches. Biocatalysis for sustainable "green" production of pharmaceuticals and specialty chemicals. Engineering organisms to convert biomass to fuels and chemicals.
- *Fluid Mechanics and Transport Processes.* Mechanics of polymeric liquids, microstructured fluids, colloidal dispersions, and 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.
- *Electronic Materials and Devices.* Plasma processing of semiconductors, pattern etching and deposition. Modeling and simulation of pattern-dependent effects. Chemical reaction dynamics of plasma-surface interactions.
- *Microplasmas.* Sources of reactive radicals and ions at high pressures. Microreactors for gas conversion/pollutant destruction. Synthesis of nanocrystals. VUV-excimer radiation emitters.
- *Nanotechnology.* Aerosol synthesis of nanoparticles for microelectronic and photovoltaic applications. Nanoprobes, nanomechanics, nanofluidics. Crystallization in carbon nanotube cavities. Synthesis and characterization of quantum dots and nanostructural materials. Environmental consequences of nanotechnology.
- *Environmental Chemical Engineering.* Physics and chemistry of atmospheric gases and aerosols, bioaerosols, climate change.
- *Aerosols and Colloids.* Nucleation and growth of particles. Particle formation and reactions. Structure and properties of colloidal dispersions. Aerosol and colloidal particle characterization.
- *Applied Mathematics and Computational Physics.* Supercomputer applications in fluid mechanics and environmental modeling. Concurrent computing. Asymptotic analyses of transport processes.
- *Physics of Complex Fluids.* Structures, phase transitions, and dynamics of polymers, liquid crystals, surfactant solutions, and suspensions.

- *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 (scheduled to open in early 2010), 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 physics, theoretical chemistry, and chemical biology. Research areas include chemical synthesis and catalysis, chemical dynamics and reaction mechanisms, biochemistry, bioinorganic, bioorganic and biophysical chemistry, and materials chemistry. Chemical research at Caltech is also highly interdisciplinary, mirroring the increasing importance of molecular understanding in many fields of science. Active interactions exist between chemistry and other disciplines at Caltech, especially applied physics, biology, chemical engineering, environmental science, geological and planetary sciences, and materials science. Major initiatives are fostering broad collaborations in energy and environment, molecular medicine, and nanomaterials.

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

Areas of Research

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

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

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

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

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

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

Physical Facilities
The laboratories of chemistry consist of eight units providing space for about 25 research groups, including 300 graduate students and postdoctoral research fellows. Crellin and Gates Laboratories house several research groups, the divisional instrumentation facilities, and the divisional administrative offices. Synthetic research groups occupy the Arnold and Mabel Beckman Laboratory of Chemical Synthesis and Church Laboratories. The Braun Laboratories and the Broad Center for the Biological Sciences house biochemical groups and are shared with the Division of Biology. 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 will soon join several chemical engineering colleagues in the nearly completed 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; applied mechanics; earthquake engineering; finite element analysis; 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; and seismic risk and structural reliability.

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 Franklin 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.

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

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

COMPUTER SCIENCE

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

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

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

- *Physical Implementation of Computations.* Computations must ultimately be implemented in some physical medium (e.g., semiconductor electronics, DNA self-assembly, quantum states of elementary particles, molecular electronics). Developing robust disciplines, abstractions, and methodologies that allow the design of reliable computing substrates has been a focus of the department since its inception. Caltech has been a leader in the early development, engineering, and design of very large scale integrated (VLSI) circuits. Beyond VLSI, efforts are under way to understand quantum, biomolecular, and molecular electronic substrates as possible media for future computing machines. As was the case with semiconductor electronics, Caltech computing can draw on the world-class expertise of its biology, physics, and chemistry departments as it tackles the many challenging opportunities that these new substrates present.
- *Systematic Design*. A key theme in the Caltech computer science department is the systematic design of systems at all levels. This theme shows up in the design of numerical algorithms for physical simulation and computer graphics, design of concurrent and distributed systems, abstractions for physical computing substrates, design of learning systems, design of programming languages, automated optimization of computations for both software and hardware implementation, as well as control and optimization of networks. The success of computer systems has allowed the building of systems of unprecedented scale and complexity. These systems can only be understood and managed if we carefully contain the complexity involved. We can only hope to create and optimize efficient computing artifacts by systematically defining and exploring their design space. This does not say that system design is not a creative endeavor, but rather that careful design allows us to expose the places where creativity is most needed, and to carefully assess the impact of new ideas and techniques.
- *Concurrency.* The physical world is highly parallel. Caltech computer science has embraced concurrency as a fundamental

feature of computing systems from its inception. Within the department, parallelism is a theme at all levels, from physical circuits, through tightly coupled, concurrent multiprocessors, through distributed systems, up to Internet-wide computing systems and beyond. Disciplines and systematic design for defining and managing the potentially complex interactions in parallel systems is a key focus.

- *Robust Modeling of Physical Systems*. Caltech computer science also has a unique focus in developing rigorous and robust models of the physical world. These models are mathematically and physically sound, often derived from differential geometric principles, and serve as a basis for computer graphics and vision research, as well as the simulation of mechanical, optical, and biological systems.
- *Theory*. A key component of systematic design is a strong theoretical understanding, which provides a basis for synthesis, analysis, and verification. The theory of computation focuses on deep mathematical problems, many of which have substantial technological impact. Theory is not relegated to a single group at Caltech, but rather forms an integral part of all disciplines (learning, VLSI, systems, graphics, programming languages, cryptography, etc.). As such, it has a strong connection to actual practice in each domain. Theory in computer science at Caltech includes traditional fields such as complexity analysis and semantics, theories of numerical computation, optimization, probability, and game theory.
- *Interdisciplinary Research*. Computation enables better control and understanding of the physical world—two ubiquitous themes at Caltech. We have already noted the intimate way in which computer science interacts with the physical sciences to physically build computations. Computer simulations, modeling, and analysis are now key enablers, allowing all fields of science to advance rapidly. Modern mechanical and aeronautical systems are enabled by vast computational processing for sensing and control. Furthermore, insights into computational management of information helps us understand information processing issues in natural systems (e.g., cells and neurons) and build hypothetical models that advance our understanding of natural cognition. Economic analyses play an important role in the design of computing systems and, in addition, research on information systems impacts business and economics. These relations provide many opportunities for scholars in computer science to work closely with colleagues throughout Caltech. The centers for information science and technology facilitate and promote such interdisciplinary research (see http://www.ist.caltech.edu).

Physical Facilities
The computer science department has excellent computing facilities ranging from high-performance workstations to multiprocessors and supercomputers. The department maintains a large computer lab open to students, and offers a large collection of software for a wide range of applications. The inventory of computers and graphics cards is frequently upgraded, and 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.

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 is designed to meet the challenge of educating students both in the mathematical methods of control and dynamical systems theory and their applications to engineering problems.

Automatic control is an enormously successful field that affects every aspect of our lives. A combination of technological developments, economic pressures, and research advances has promoted control into a central position in technology, and over the next several decades, the impact of automatic control systems will continue to grow. The applications we have seen so far—such as cheap and fast computer disk drives, active vehicle suspension control, fly-by-wire aircraft, highly integrated manufacturing facilities, and manned and unmanned space systems—are only the beginning of this trend.

The rapid development of dynamical systems theory as an intellectual discipline over the past 10 years has been equally striking. Stimulated by the discovery of the phenomenon of “deterministic chaos,” the “dynamical systems approach” has been adopted in a variety of diverse engineering disciplines (e.g., chemical, mechanical, electrical, civil, and aerospace), as well as the physical, biological, and social sciences. At the same time, dynamical systems continues to enjoy strong links with pure and applied and computational mathematics.

While research in both control and dynamical systems is inherently interdisciplinary and crosses many traditional engineering and scientific boundaries, their relationship is much deeper. As theoretical disciplines, they are moving together rapidly. The mathematical background required to do research in either control or dynamical systems is nearly identical and can be difficult to obtain within traditional curricula in engineering and mathematics. The CDS option provides a coherent and complete graduate curriculum with corresponding research opportunities, both theoretical and applied.

Areas of Research

Theoretical research is conducted in all aspects of control, with emphasis on robustness; multivariable and nonlinear systems; optimal control; decentralized control; modeling and system identification for robust control; control of Hamiltonian and Lagrangian systems; and control of nonholonomic mechanical systems. Techniques from operator theory, differential geometry, dynamical systems, and computer science are combined to study control problems in a wide variety of areas. A central theme is the role of uncertainty and robustness, and the development of a unified theory for modeling, system identification, analysis, and synthesis of nonlinear control systems.

The CDS research program in nonlinear dynamics has two components: one mathematical and the other driven by specific areas of applications in science and engineering. The main thrust of the mathematical research is to develop mathematical methods for studying the dynamics of the types of nonlinear dynamical systems that arise in science and engineering. Active areas include developing methods for detecting and describing chaotic phenomena; local and global bifurcation theory; homoclinic and heteroclinic motions; Hamiltonian dynamics; geometric mechanics and mechanical systems with symmetry; phase space transport theory; geometrical dynamical systems theory for infinite dimensional systems; computational methods for visualizing higher dimensional phase space structures; and statistical methods for the description of chaotic dynamics.

Active application areas at Caltech include complex systems in networks and biology; multiscale modeling and simulation applied to biological systems, fluids, and solids; vortex structures in complex fluid flows; mixing and transport processes in fluids; classical dynamics of molecules; phase space structure and mechanisms that enhance and inhibit transport and energy flow; turbomachines and complex combustion systems; nonlinear flight dynamics for highly maneuverable aircraft; robotic locomotion and manipulation; and the design of autonomous systems.

ELECTRICAL ENGINEERING

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

Areas of Research and Physical Facilities

Substantial experimental laboratory facilities, housed mainly in the Moore Laboratory of Engineering, are associated with each of the research fields described below.

1. *Quantum Electronics and Optical Communication* (Yariv)—Research projects in progress include the generation and control of ultrashort pulses, integrated optoelectric semiconductor circuits, semiconductor injection lasers, molecular beam epitaxy growth of submicron GaAs/GaA1As structures for optoelectronics and electronics, ultrafast ($<10^{-12}$s) semiconductor lasers, theoretical and experimental quantum optics–light squeezing, studies of noise and pulse propagation in optical fibers, and theoretical and experimental studies of new devices and phenomena involving fiber grating, with special emphasis on optical filters for wavelength division multiplexing in optical fiber communication. A new direction being launched is to develop the use of semiconductor lasers in optical phase-lock loops for phase demodulation of optical beams and for a variety of phase-coherent applications in optical communications.
2. *Communications and Signal Processing* (Effros, Hassibi, Ho, Low, Vaidyanathan)—Theoretical and computer experimental work in a wide range of information, communication, and signaling problems. Current research emphases are in error control coding, modulation, and capacity calculations for channels that occur in communication networks, multiuser mobile and cellular radio, and deep-space communications; network communications, including 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; applications of neural networks to communication and signal processing problems; traffic modeling, routing, and network architectures for mobile services and ISDN; and design and simulation of single-rate and multirate digital filters and filter banks to minimize the number of computational

operations for a given accuracy. Digital filter banks, subband coding, wavelet transforms, multidimensional multirate signal processing. Possibilities exist for joint work with microsystems, wireless communication, digital signal processing, and data compression.

3. *Control* (Doyle)—Theoretical research is conducted in all aspects of control, with emphasis on robustness, multivariable and nonlinear systems, and optimal control. Theoretical developments are tested using the latest in computer and experimental facilities in a wide variety of application areas. Opportunities on campus, at Caltech's Jet Propulsion Laboratory, with industrial sponsors, and at NASA laboratories include control problems associated with large flexible space structures, refinery systems, flight control, robotics, control of unsteady flows, and various other aerospace and process control applications.
4. *Wireless Sensing and Communications* (Hajimiri)—Circuits and system design for wireless communication using integrated circuit technology, fully integrated silicon-based mm-wave circuits and phased array transceivers, novel modulation techniques using integrated electromagnetic structures, high-frequency integrated power generation, equalization for wireline communications, and multimode reconfigurable systems. This area of research also includes analysis and design of communication 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.
5. *Learning Systems and Computational Finance* (Abu-Mostafa)—The Learning Systems Group at Caltech studies the theory, algorithms, and applications of automated learning. The theory of learning uses mathematical and statistical tools to estimate the information (data and hints) needed to learn a given task, and the computational aspects of learning. The algorithms deal with learning mechanisms in different models, such as neural networks, and different learning protocols. The applications of learning are very diverse. The group has emphasized computational finance applications, where learning is used in financial forecasting, risk analysis, and derivative pricing. Other recent applications include pattern recognition and medical diagnosis.
6. *Energy* (Rutledge)—Assessment of future supplies of oil, gas, and coal. The approach is historical; curve fits to the production history are used to make projections of ultimate production, by which is meant total production, past and future. We consider the implications of these projections for alternative energy sources, and for future climate.

7. *MEMS/NEMS Sensors and Actuators* (Tai)—We exercise various MEMS, VLSI, and micro/nanotechnologies to physically fabricate miniature integrated devices. Current research includes intergrated biochips, microfluidic chips, smart skins, neuroprobes, micropower generators, etc. High-level system integration and hands-on fabrication are especially emphasized for our students in the Caltech Micromachining Laboratory.
8. *Digital Signal Processing* (Hassibi, Vaidyanathan)—Theoretical and computer oriented work on a wide variety of problems in digital signal processing. Multirate systems and filter banks, wavelets, filter design, quantization in signal processors, adaptive signal processing, statistical signal processing, robust filtering, multidimensional multirate systems, and wavelet transforms. Digital filter banks, digital communication systems, multidimensional multirate signal processing. Image processing, digital halftoning, and denoising.
9. *Computational Vision* (Perona)—Theoretical and experimental research on the computational principles underlying vision processes. Psychophysics and modeling of the human visual system. Theory and applications of computer vision. Current emphasis on visual object recognition; vision-based human-computer interfaces; perception and modeling of human motion and activities; 3-D photography, perception, and modeling of shapes. Areas of collaboration include learning theory, computer graphics, neurophysiology, psychology, applied probability, robotics, geometry, and signal processing.
10. *Nanofabrication and Design of Ultrasmall Devices* (Scherer)—High-resolution lithography and dry etching allow the miniaturization of structures to below 10 nanometers. Using these techniques, ultrasmall optical, magnetic, and fluidic structures can be constructed. Current research includes the design and fabrication of nanocavity lasers; photonic-crystal waveguides and modulators; nanomagnet arrays; nonmechanical oscillators; and microfluidic pumps, valves, and networks on biochips.
11. *Distributed Information Systems* (Bruck)—Research on synthetic and natural distributed information systems, including information systems in storage and communications (the synthetic part) and the development of abstractions for the analysis and design of biological regulatory networks (the natural part). The information systems work includes developing efficient array codes for increased reliability of RAID storage systems, schemes for representing information in magnetic recording and optical communications, and methods for representing and protecting information in flash memories. The mathematics of biology-related work includes the development of a calculus for representing computation in gene regulatory networks: for example, demonstrating for the first time that an approximate general computation can be achieved using a finite set of chemical reactions, provided that they operate in a stochastic

manner. Past projects include the RAIN (Reliable Array of Independent Nodes) project. The RAIN technology resulted in a spin-off company called Rainfinity (acquired in 2005 by EMC), which focused on software products for the management of network information systems.

12. *Data Compression* (Effros)—Theoretical analysis and practical design of algorithms for efficiently representing information for communication, storage, and processing. Current work focuses on the special challenges introduced by emerging applications such as network communication systems. Examples of areas of investigation include the theory and practice of optimal data compression for systems containing multiple encoders, multiple decoders, or both, and adaptive or universal compression systems. Results range from theoretical performance bounds to practical coding algorithms. 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, digital signal processing, and computational vision.
13. *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 multiband systems, single-chip spectrum analyzers, performance limitation of A/D and D/A data converters, and robust circuit-design techniques. Projects also include mm-Wave silicon-based circuits and arrays, self-healing circuits, high-frequency power generation in CMOS, analysis and design of distributed circuits, multimode reconfigurable systems, as well as modeling of the effect of substrate and supply noise in large integrated circuits and design techniques to minimize their effect, examination of integrated passive structures and their fundamental performance limits, and noise modeling in amplifiers, mixers, and oscillators. More information can be found at http://www.chic.caltech.edu.
14. *Networking* (Low)—Modeling, analysis, control, optimization, simulation, and implementation of networks and protocols and networked computing. Current research focuses on congestion control, active queue management, multicast, web performance, resource allocation, and fundamental issues in networked computing, control, and communication. More information at http://netlab.caltech.edu.
15. *Wireless Communications* (Hassibi)—Theoretical research on link, system, and network aspects of wireless communications. Current areas of interest include time-varying channel model-

ing; 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.

16. *Biophotonics* (C. Yang)—Experimental research on imaging and extraction of information from biological targets through the use of light. Current areas of interest include optofluidics, needle endoscopy, phase conjugation–based turbidity suppression, optical coherence tomography, multiphoton imaging, quadrature homodyne interferometry, and microscopy. More information can be found at http://www.biophot.caltech.edu.
17. *Mixed-signal Engineering* (Emami)—Design and implementation of high-performance analog and digital circuits for wire line 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 microelectronics for biological systems and neurosciences. Tools and design methodologies for mixed-signal circuits and systems, with the emphasis on modeling and understanding of the fundamental limits and physical properties.
18. *Integrated Biosensors* (Hajimiri)—Use of intergrated circuits for novel detection techniques of biological matters using various sensing modes (e.g., electrical, magnetic, optical) and leveraging the complexity of silicon-based integrated circuits to create state-of-the-art sensitivity for such sensors for a variety of bio molecules, such as DNA and proteins. This area also includes analysis of the dynamics and kinetics of such sensors for a variety of applications, including microarrays, point-of-care sensors, and other medical equipment.

ENERGY SCIENCE AND TECHNOLOGY

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

ENVIRONMENTAL SCIENCE AND ENGINEERING

This interdisciplinary graduate program is concerned with earth system science and engineering. Complete information is available at http://www.ese.caltech.edu.

At the heart of the ESE program are three core areas of research expertise: environmental physics, environmental chemistry, and environmental biology. Research and instruction emphasize basic scientific studies that underlie new solutions to challenging environmental problems from atomic to global scale. These include urban, regional, and global air quality; water supply and water quality control; hazardous waste treatment; microbial ecology; and global environmental and climate change.

Among the academic disciplines central to the program are atmospheric and aquatic chemistry; environmental fluid mechanics; environmental and geochemical microbiology; dynamic meteorology; oceanography and hydrology; aerosol physics and chemistry, chemical reaction engineering, and chemical kinetics and photochemistry. Courses are offered in the environmental science and engineering program and in other related programs of the Institute. Faculty members participating in this interdisciplinary program are from the Divisions of Engineering and Applied Science, Chemistry and Chemical Engineering, and Geological and Planetary Sciences.

Areas of Research

Examples of recent and current research are theoretical and experimental studies on trace elements and individual chemical compounds in the environment; aerosol chemistry and physics; cloud chemistry; photochemistry of important trace gases; studies of the emissions sources and fate of organic chemicals in the atmosphere;

regional air pollution modeling and control; global-scale modeling of tropospheric chemistry and the carbon cycle; marine geochemistry; geochemical studies of paleo ocean circulation; trace-gas geochemistry; microbiology of iron-reducing organisms; termite-microbe symbiosis and its impact on trace-gas dynamics; cultivation of novel microbes with novel properties; antagonistic interactions among competing soil microbes; climate studies including transport of heat and moisture by the atmosphere; and monsoon dynamics.

Physical Facilities

The laboratory experimental work in environmental science and engineering is carried out across the Caltech campus with a wide variety of modern instrumentation in the various laboratories described below.

The atmospheric chemistry and aerosol laboratory includes a state-of-the-art facility located on the roof of the Keck Laboratory that has been specially designed for studies of the photochemical reactions of gaseous and particulate pollutants. Dual 28 m^3 indoor irradiated reaction chambers are used for direct simulations of atmospheric conditions using carefully prepared mixtures of hydrocarbons, nitrogen oxides, and aerosols. Both gas-phase chemistry and the formation of aerosol particles are probed with this system.

Analytical instrumentation includes monitors for major gas-phase trace gases, gas chromatography, gas chromatography with mass spectrometry, and the resources of the Environmental Analysis Center for detailed chemical analysis of gas and aerosol samples. Measurements of aerosol particle formation and growth in the smog chamber experiments and in field studies are performed using the scanning electrical mobility spectrometer, a fast-response, high-resolution particle-sizing instrument developed at Caltech, along with more conventional particle measurement techniques (optical particle counters, cascade impactors, condensation nuclei counters, and filter samplers). A novel aerosol mass spectrometer is used for molecular speciation of aerosols.

Flow reactors are used for controlled studies of nucleation processes, and to probe the dynamics of agglomerate aerosols. Equipment is available sufficient to conduct field experiments involving the measurement of atmospheric particulate matter concentration, chemical composition and size distribution, and gaseous pollutant concentration, simultaneously at up to 10 monitoring sites.

Caltech, in conjunction with the Naval Postgraduate School in Monterey, California, operates the Center for Interdisciplinary Remotely Piloted Aircraft Studies. This center operates research aircraft for atmosphere science studies, including a Twin Otter aircraft instrumented to carry out state-of-the-art measurements of atmospheric aerosol and cloud properties and composition. Caltech faculty and graduate students regularly participate in large, international field programs in atmospheric chemistry and aerosols using the aircraft available in the Center.

The environmental chemistry and aquatic chemistry laboratories and the Environmental Analysis Center are equipped for chemical analysis by electrochemistry, plasma emission mass spectrophotometry, gas chromatography, high-performance liquid chromatography, fluorescence spectroscopy, infrared spectrometry, gas chromatography–mass spectrometry (GC-MS), liquid chromatography–mass spectrometry (LC-MS), high-resolution MS/MS/MS, ATR-FTIR, electrospray mass spectrometry, supercritical fluid extraction (SCF/MS), multicomponent UV-visible spectrophotometry, electrophoresis chromatography, gradient-elution ion chromatography, gel permeation chromatography, total organic carbon analysis, and, for physical characterization of aqueous particles by light scattering, electrophoresis and electrical particle size analysis. The Environmental Analysis Center operates 14 mass spectrometry systems.

The atmospheric photochemistry laboratory has a number of lightsources and detectors for investigation of atmospheric chemistry. Instrumentation development activities include design of optical and mass spectrometers for environmental analytical chemistry.

The environmental microbiology laboratory includes a facility for the preparation of bacterial media, as well as equipment for the isolation, cultivation, and physiological characterization of fastidious and anaerobic microbes, DNA isolation and manipulation, DNA sequence data manipulation and analysis, protein purification and enzyme assays, and culture field analyses. In addition, access is available to several electron microscope facilities on campus, as well as the oligonucleotide probe synthesizer and the microprotein sequenator.

The option provides students with access to scientific computing through advanced supercomputers operated by the Division of Geological and Planetary Sciences.

GEOLOGICAL AND PLANETARY SCIENCES

Students and faculty in the Division of Geological and Planetary Sciences study the earth and planets to understand their origin, constitution, and development, and the effect of the resulting physical and chemical 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, geology, geobiology, geochemistry, 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 the 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 the 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 the 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 the 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 the 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 512-node (4096 core) supercomputer used by students and faculty for Earth and planetary science 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; tunable laser spectrometers; high-temperature furnaces and high-pressure apparatus including piston-cylinder, multi-anvil, diamond anvil, and shock-wave facilities. Our most advanced analytical tools are operated by our Center for Cosmochemical and Geochemical Microanalysis. Cooperation with other departments on campus, such as materials science and environmental science and engineering, provides access to additional instrumentation for sample preparation and analysis.

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

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

HISTORY AND PHILOSOPHY OF SCIENCE

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

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

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

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

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

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

Areas of Research

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

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

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

INDEPENDENT STUDIES PROGRAM

Independent Studies is an educational alternative for undergraduates whose goals cannot be satisfied with a normal undergraduate option. The student gathers a three-person faculty committee, representing at least two divisions of the Institute, and chooses his or her own scholastic requirements under this committee's supervision. Approval must also be obtained from the Curriculum Committee, a standing committee of the faculty. The independent 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 223.)

INFORMATION SCIENCE AND TECHNOLOGY

Information Science and Technology (IST) is a multidivisional research area that includes participants from the Divisions of Biology, Chemistry and Chemical Engineering, Engineering and Applied Science, Humanities and Social Sciences, and Physics, Mathematics and Astronomy. 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
Research centers associated with IST include the Lee Center for Advanced Networking, the Center for Neuromorphic Systems Engineering, the Center for Biological Circuit Design, the Center for the Mathematics of Information, the Center for the Physics of Information, and the Social and Information Science Laboratory.

MATERIALS SCIENCE

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

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

Physical Facilities
Research by the faculty, graduate students, and a few advanced undergraduates is conducted in the W. M. Keck Laboratory and the Steele Laboratory. Material-preparation facilities include equipment for physical vapor deposition under ultrahigh vacuum conditions, melting, casting, and rapid solidification, equipment for the processing of ceramic powders, and high-energy ball milling. Facilities for the characterization of materials include an extensive array of X-ray diffraction instruments including a single crystal diffractometer, three X-ray powder diffractometers with high-performance, position-sensitive detectors, impedance spectrometers for transport and dielectric measurements, Mössbauer spectrometers, differential scanning calorimeters and differential thermal analyzers, thermogravimetric analyzers, and several test systems for the measurement of mechanical properties. A microscopy facility has been built around an FEI Tecnai TF30 300-keV transmission electron microscope with high resolution and analytical capabilities. Another analytical 120-keV transmission electron microscope is dedicated to materials research. In addition to the equipment within materials science, a wide range of mechanical and microstructural characterization facilities are available elsewhere at Caltech.

MATHEMATICS

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

- *Algebra*. Finite group theory, algebraic groups, representation theory, symmetric functions, algebraic K-theory.
- *Algebraic Geometry.* Moduli spaces, birational geometry, Hodge theory, Calabi-Yau varieties, arithmetic geometry.

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

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

MECHANICAL ENGINEERING

Mechanical engineering at Caltech concerns itself with the boundaries between traditional disciplines of science and engineering in order to develop new understanding and advanced technology to address contemporary problems. Mechanical engineering encompasses three broad areas: mechanics (including active materials, fracture mechanics, and mechanics of materials), mechanical systems (including control and analysis of dynamic systems, engineering design of electromechanical systems including microfluidic and optofluidic devices, kinematics, optimization, robotics, and structural design), and fluid and thermal systems (including acoustics, cavitation, chemical vapor deposition, combustion, fluid flow and hydrodynamic instabilities, heat and mass transport, multiphase and multicomponent flows, propulsion, and turbulence). These areas are applied to a rich diversity of problems including bioengineering, control of aircraft engines, design of vehicle structures, granular flows, earthquake occurrence, hyper-redundant robots, jet noise reduction, locomotion and grasping, medical applications of robotics, navigation algorithms, structured design of micro-electromechanical systems (MEMS), thin-film deposition, transportation systems, propulsion systems, and rapid assessment of early designs.

The educational program in mechanical engineering at Caltech prepares students for professional practice and research in an era of rapidly advancing technology. It combines a strong background in the basic and engineering sciences with laboratory and design experience. 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 are an integral part of the mechanical engineering option. In general, work pursued within the mechanical engineering option emphasizes aspects of mechanics that are concerned with mechanical behavior of homogeneous and heterogeneous solids, bridging temporal and spatial scales, thin film, MEMS, active materials, composites, dynamic deformation, fracture and frictional sliding of solids, computational modeling, and advanced experimental diagnostic techniques. Additional interests include the mechanics of heterogeneous geological systems.
- *Mechanical Systems and Engineering Design.* Activities in these areas encompass a broad range of traditional 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 design theory and methodology, imprecision in engineering design, engineering system design, MEMS design, kinematics, robotics, autonomous systems, control of mechanical systems, computer-aided design, and simulation.
- *Thermal Systems and Fluid Dynamics.* This area encompasses a broad spectrum of research activities, including convective heat transfer (packed beds, moving granular media, rotating flows), chemical vapor deposition of thin films, computational fluid dynamics including molecular dynamic simulations, acoustics of turbulent flows, explosion dynamics including deflagrations, detonations, and shock waves, two-phase flow including colloidal dispersions, cavitation, turbomachines for flow of liquids and rocket propellants and combustion, and transport phenomena in micro/nanofluidic systems including phase transitions, fluid instabilities in free surface flows, and Marangoni and thermocapillary forcing in thin liquid films.

Physical Facilities

Laboratory facilities are available in a number of areas, including control of mechanical systems, computer-aided design, flow visualization, heat transfer, liquid phase turbomachines, thin-film deposition, robotics, and hydrodynamic water tunnels. These facilities are shared by research groups collaborating with applied mechanics, applied physics, civil engineering, and control and dynamical systems.

PHYSICS

Areas of Research
Students in physics will find opportunities for research in a number of areas where members of the faculty are currently active, including those listed below. Physics research at Caltech is often done in collaboration with scientists in the departments of applied physics, astrophysics, planetary science, engineering, chemistry, biology, and other departments, as well as with collaborators at other universities and laboratories. Additional research programs and more detailed information can be found on the Caltech physics department website.

- *Experimental Elementary Particle Physics.* Activities in elementary particle physics are aimed primarily at finding physics beyond the Standard Model. Experimental efforts employ hadronic colliders, e+e- colliders, and neutrino beams at several international facilities. Current experiments include the Large Hadron Collider at CERN, which is searching for the Higgs boson and physics beyond the Standard Model; the MINOS and Nona experiments at Fermilab, studying long baseline neutrino interactions; the BABAR and follow-up experiments, searching for new physics in CP-violating and other rare processes in B meson and t lepton decays.
- *Theoretical Elementary Particle Physics.* The particle theory group studies the unification of interactions based on string theory, the detailed properties of hadrons described by QCD, the quantum properties of black holes, the foundations of cosmology, including dark matter and dark energy, and other aspects of mathematical physics.
- *Nuclear Physics.* The interests of the nuclear group include understanding the detailed properties of neutrinos and performing precision nuclear measurements to search for physics beyond the Standard Model. Neutrino oscillations are investigated at off-campus facilities using accelerators and antineutrinos produced in reactors to provide detailed information on the relative neutrino masses and mixing properties. Precision measurements of neutron decay allow sensitive searches for new physics, while measurements of the neutron electric dipole moment may help explain the dominance of matter over antimatter in the universe.

- *Observational Astrophysics.* Research in this area covers a broad range of topics using observational tools covering the entire electromagnetic spectrum. The high-energy astrophysics group at the Space Radiation Laboratory (SRL) uses X-ray and gamma-ray detectors aboard spacecraft and balloons to investigate energetic processes from compact astrophysical objects, including gamma-ray bursts from neutron star and black hole systems, supernova and hypernova dynamics, and the development of stars and galaxies in the early universe.

  The cosmic ray group at SRL uses data from a variety of spacecraft to study the composition of energetic particles arriving from the sun, the local interstellar medium, and beyond, in order to understand the origin and acceleration of energetic particles in space.

  The ultraviolet astronomy group uses satellite observations, such as from the GALEX spacecraft, to explore the ultraviolet sky. Studies include the birth and death of stars, galaxy dynamics and evolution, and other areas.

  The submillimeter astronomy group studies star formation, interstellar gas, galaxies, and quasars using the Caltech Submillimeter Observatory and other facilities. Far-infrared observations are made using NASA's Sofia Observatory. An active program is also underway to develop new superconducting detector technologies for use at these wavelengths, in collaboration with scientists at the Jet Propulsion Laboratory.

  The infrared astronomy groups studies a host of astrophysical phenomena using Caltech's Palomar Observatory, the twin 10-meter optical telescopes at the Keck Observatory, and observations from the Spitzer Space Telescope. Caltech also manages the Spitzer Science Center on campus.
- *Theoretical Astrophysics.* The TAPIR (Theoretical Astrophysics Including Relativity) group carries out research on an ever-changing list of topics, including high-energy astrophysics and the physics of black holes and neutron stars, gravitational-wave astrophysics, cosmology, the formation of stars and galaxies in the early universe, and general relativity.
- *Cosmology*. The observational cosmology group explores the structure and dynamics of the early universe using precise measurements of the cosmological microwave background radiation from detectors on the ground, on balloons, and on spacecraft. Efforts to directly detect dark matter are also underway. 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 vari-

ety of astrophysical sources. Theoretical studies are aimed at developing sensitive data analysis techniques and calculating G-wave signals from sources such as coalescing black holes and neutron stars.

- *Condensed-Matter Physics.* Areas of interest include correlated electron systems, 2-D matter, phase transitions, atomic and excitonic Bose condensation, nanomechanical and nanoelectronic systems, biosensors, quantum electromechanics, phonon physics, high-temperature superconductivity, graphene and carbon nanotube systems, quantum entanglement, dynamics of disordered systems, chaos, pattern formation, and systems far from equilibrium. Resources include numerous labs in the Caltech physics department, at the Kavli Nanoscience Institute at Caltech, and at the Jet Propulsion Laboratory.
- *Quantum Optics and Information.* Research on campus and at the Institute for Quantum Information at Caltech includes studies of the nature of quantum computation and quantum information, cavity quantum electrodynamics, algorithms and error correction techniques in quantum computation, and generally how quantum physics can be harnessed to improve the acquisition, transmission, and processing of information.

Physical Facilities

The physics and astrophysics departments and laboratories are mainly housed in six buildings on campus: the Norman Bridge Laboratory, the Alfred P. Sloan Laboratory of Mathematics and Physics, the W. K. Kellogg Radiation Laboratory, the George W. Downs Laboratory of Physics, the C. C. Lauritsen Laboratory of High Energy Physics, and the Cahill Center for Astronomy and Astrophysics. Off-campus astronomical facilities include Palomar Observatory, the Keck Observatories, Owens Valley Radio Observatory, the Caltech Submillimeter Observatory, the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and the Laser Interferometer Gravitational-Wave Observatory (LIGO).

SOCIAL SCIENCE

The social science program at Caltech is highly interdisciplinary, integrating economics, political science, quantitative history, law, anthropology, and psychology. It makes extensive use of mathematical modeling, laboratory experiments, and econometric techniques. Social science at Caltech strongly emphasizes the understanding and analysis of the relationships between individual incentives, political and economic institutions, and public policy.

Areas of Research

Caltech social scientists are leaders in the field of laboratory experimentation. They have focused upon the behavior and design of auctions and auction-like mechanisms, public goods provision, interpersonal bargaining, and committee decision making. Considerable laboratory experimentation also focuses upon the workings of financial markets, and seeks to elucidate basic principles that underlie the pricing of assets, trading, and information aggregation in these markets. Many of these experiments are conducted through the use of networked computers in the William D. Hacker Social Science Experimental Laboratory.

In recent years, new avenues of experimentation in social science have emerged with advances in neuroscience. Utilizing fMRI brain-imaging, eye-tracking, and other measurement technologies, research at Caltech has begun to explore the neural foundations of decision making in game theoretic and market settings. The real world provides another setting for experimental research, and Caltech social scientists have conducted game theoretic-based experiments involving a wide variety of subjects, ranging from urban Americans to African villagers.

In the area of economic theory, research at Caltech has played a major role in the design of new institutions that more efficiently allocate resources and provide public goods. There has also been considerable research at Caltech on developing better theoretical and statistical models of individual choice behavior.

Political scientists at Caltech focus primarily upon quantitative analyses of voting, legislative behavior, and public policy. They draw heavily upon techniques and approaches used in a variety of other disciplines, such as economics, statistics, and legal studies. During the past decade Caltech faculty members have been active contributors to the Voting Technology Project, a joint Caltech-MIT research effort that evaluates the performance and reliability of U.S. balloting technology, registration systems, and election administration. Caltech political scientists have also pioneered techniques for the detection of vote fraud and other election anomalies.

As in the case of economics and political science, historical research conducted at Caltech employs mathematical modeling and sophisticated statistical techniques to attack a wide range of historical questions. These include the development of capital markets in Europe, the impact of racial discrimination in the United States, the causes of recurrent financial crises in capitalist economies, and the determinants of economic growth.

Information for Undergraduate Students

The undergraduate program leads to a four-year Bachelor of Science degree. Admitted students matriculate in the fall term only. Caltech does not have a summer session or part-time program, and cannot consider you if you already have a bachelor's degree from another college, university, or the equivalent. If you have matriculated at any college, university, or the equivalent in a program leading to any degree, you will probably be required to apply as a transfer student, and should read the requirements in the section titled "Transfer Admissions."

ADMISSION TO THE FRESHMAN CLASS

Students are admitted to the freshman class on the basis of strong academic performance in a rigorous course of college preparatory study, especially in the areas of math and science; results of the SAT or ACT, and one SAT science subject test and the SAT mathematics level 2 test; teacher and counselor evaluations; personal characteristics; a demonstrated interest in math, science, or engineering; and information provided on the application.

Applying
Information on the application process can be found on the admissions office website at http://www.admissions.caltech.edu. Students are encouraged to apply online through the Common Application. For further information on admission, please call (626) 395-6341 or e-mail ugadmissions@caltech.edu. To be considered for admission, applications to the freshman class must be submitted online or postmarked by January 2.

Early Action
The Early Action application process requires that the completed application be postmarked or submitted online by November 3. 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, Chemistry, or Physics.

Information regarding the College Board examinations can be found in the Bulletin of Information, which may be obtained without charge at most high schools, or by contacting the College Board, 45 Columbus Avenue, New York, NY 10023-6992; (609) 771-7600; sat@info.collegeboard.org; or http://www.collegeboard.com. For ACT, 500 ACT Drive, P.O. Box 168, Iowa City, IA 52243-0168; (319) 337-1270; http://www.act.org.

Essays
The essays, which are required as a part of the application, are intended to provide students the opportunity to communicate their interests, experiences, and background. Since Caltech is interested in learning about each applicant, the essays are viewed as an important part of the admission decision process.

Evaluations
Two evaluations and a Secondary School Report are required. One must be from a math or science teacher, and one from a humanities or social science teacher (see the instructions in the application). A Secondary School Report must be filled out by the applicant's high-school counselor or other school official.

Additional Material
Descriptions of research projects and hands-on science and engineering experience are helpful, as is material that demonstrates experiences outside math and science. Additional material should be identified with name and date of birth.

Acceptance
Caltech is a National Association for College Admissions Counseling member and therefore agrees to comply with the candidate's reply date of May 1. Places in the entering class will not be held after May 1. Early Action applicants will be informed of their status in mid-December, and Regular Decision applicants will be informed by April 1.

Deferral of Entrance
For reasons of travel or work, Caltech will consider requests from admitted students for a one-year deferral of entrance. Students

who request a deferment must submit a written request stating the purpose of postponement.

Advanced Placement, International Baccalaureate, and College Credit
Caltech encourages all prospective undergraduate applicants to prepare by challenging themselves with the most rigorous course of study available, including the Advanced Placement (AP) and International Baccalaureate (IB) programs. However, college credit for AP or IB classes is not automatic. Course credit and/or placement in an accelerated program is *sometimes* granted as deemed appropriate by the department faculty. The awarding of Caltech course credit takes place at the time of registration each fall.

<u>Biology</u>
Prospective biology majors who pass both Bi 8 and Bi 9 in their freshman year are considered to have met the core requirement of Bi 1.

<u>Chemistry</u>
For those students who qualify for advanced placement in chemistry, the Institute requirement of 15 units of Ch 1 ab can be satisfied by completing with passing grades two terms of (i) Ch 21 abc (9 units each term), or (ii) Ch 41 abc (9 units each term). The student's qualifications for advanced placement in chemistry will only be determined by the performance on a placement examination to be administered in the summer prior to registration. Similarly, qualified students, with the instructor's consent, are allowed to substitute either Ch 3 b or Ch 4 a for the "core" chemistry laboratory requirement (Ch 3 a).

<u>English/Writing</u>
All incoming students (freshmen and transfers) must submit a placement essay 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 En 1 a or En 2 before enrolling in a freshman humanities class. (En 1 ab and En 2 count for general Institute credit only.)

<u>Mathematics</u>
During the summer before the freshman year, entering freshmen are asked to take a diagnostic exam in basic calculus that will determine which students will be placed in a special section of Ma 1 a for those with less complete preparation, and later take Ma 1 d; and if they are interested in advanced placement, they may also take an examination to determine whether they will begin the mathematics core sequence at an advanced level.

Normally, an entering freshman takes Ma 1 abc, Calculus of One and Several Variables and Linear Algebra. This course covers the calculus of functions of one and several variables; infinite series; vector algebra; basic and advanced linear algebra; derivatives of vector functions, multiple integrals, line and path integrals; and theorems of Green and Stokes. The course is divided into a lecture part and a recitation part that focuses mainly on problem-solving.

Students in need of additional problem-solving practice may be advised to take Ma 8 (in addition to Ma 1 a) in the first quarter.

Physics

The required freshman physics course, Ph 1 abc, is considerably more rigorous than most advanced placement work, and entering freshmen are encouraged to take Ph 1. A test is administered during the summer to aid in the organization of Ph 1; students who have performed particularly well can discuss the possibilities for advanced placement with the physics representative during orientation. A second test may then be required.

New Student Orientation

All freshmen and transfer students are expected to attend the New Student Orientation as a part of the regular registration procedure.

The orientation takes place the week prior to the beginning of classes. A large number of faculty members and upperclass student leaders participate, helping to introduce the new student to the Caltech community. The orientation period provides an opportunity for the new student to become acquainted with the campus, the Honor System governing personal conduct, and other aspects of life at Caltech. In addition, he or she can meet classmates, upperclass students, and faculty. Thus the new student can begin to feel at home at Caltech and to share in the common agreement on intellectual and moral standards before the pressure of academic work begins.

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
- Biology 1
- Humanities and Social Science electives
- Menu science class (see page 175; can be taken freshman or sophomore year)

Sophomore courses:
- Mathematics 2 ab
- Physics 2 ab or Physics 12 abc
- Additional laboratory science
- Humanities and Social Science electives

Eligibility Criteria for Admission
The Institute admits to its sophomore and junior classes a small number of students who have excellent records at other institutions of collegiate rank and who perform satisfactorily on the Caltech Transfer Admissions Entrance Examinations.

- Students must have completed their secondary school education, and have subsequently enrolled at a college or university and earned credit, in order to be considered for transfer admission.
- Transfer students are not admitted to the senior year at Caltech.
- Students who have already completed a bachelor's degree in any subject are not eligible for transfer.

Standardized Test Requirements
Transfer applicants are not required to submit SAT scores. The Test of English as a Foreign Language (TOEFL) is required of transfer applicants whose native language is not English and who have not been studying in an English-speaking country for two years or more. The TOEFL should be taken by the February test date.

Evaluation of Written English
All entering transfer students will be required to undergo an evaluation of their written English prior to enrolling.

Transfer Admissions Entrance Examinations
All applicants are required to take Caltech Transfer Admissions Entrance Examinations in mathematics and physics. Further instructions are included with the Caltech Transfer Application.

Transfer of Credit
The courses for which transfer applicants will receive credit, and the corresponding class standing, will be determined at the time of enrollment. Faculty members review each course submitted for credit on an individual basis. It is not possible, therefore, to answer questions regarding the acceptability of coursework taken elsewhere. If the standard of work taken elsewhere is uncertain, additional examinations may be required before the question of credit is finally determined.

Graduation Requirements
Admitted transfer students must meet the following requirements in order to receive a Caltech Bachelor of Science degree.

- 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 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. Questions about transfer admission and application should be directed to Transfer Information, Office of Undergraduate Admissions, Caltech, Mail Code 1-94, Pasadena, CA 91125, U.S.A.; (626) 395-6341; ugadmissions@caltech.edu. Applications may also be downloaded from the admissions website at http://www.admissions.caltech.edu.

The 3/2 Dual Degree Plan

Caltech invites students from a select group of liberal arts colleges to transfer to Caltech upon completion of their junior year. After two years in residence at Caltech, and the successful completion of our requirements, 3/2 students will be granted a Bachelor of Science degree from Caltech and a second bachelor's degree from their liberal arts college. Students may transfer into any of the Caltech options.

Students from the following institutions are eligible to apply to the 3/2 program:

- Bowdoin College (ME)
- Bryn Mawr (PA)
- Grinnell College (IA)
- Haverford College (PA)
- Mt. Holyoke College (MA)
- Oberlin College (OH)
- Occidental College (CA)
- Ohio Wesleyan University (OH)
- Pomona College (CA)
- Reed College (OR)
- Spelman College (GA)
- Wesleyan University (CT)
- Whitman College (WA)

Applications and a program description are available from the 3/2 liaison at each of the liberal arts college partners and from the Caltech Office of Undergraduate Admissions. Deadline for submission of 3/2 applications and support materials is 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.

Visiting Student Program

A limited number of students from other institutions of collegiate rank may enroll at Caltech to take classes for up to one year. These students are classified as visiting students and will not receive

Caltech degrees. Applicants should have an excellent academic record and be recommended by their home institutions. Visiting students are responsible for all costs, including Caltech's tuition and fees. Accommodations in Institute housing depends on availability. Decisions on admission are made by the Office of the Dean of Students, and prospective visiting students should contact this office by April 1 to apply for fall enrollment.

STUDY ABROAD

Study abroad allows students to gain a first-hand experience of life in countries abroad, while also gaining a broader exposure to the sciences, engineering, economics/management, the social sciences, and humanities. Students who study abroad develop an international viewpoint that transfers over to their education at Caltech and to their graduate study and future career regardless of the field they pursue professionally.

Please see the Financial Aid section of the Catalog for details on applying for and eligibility for financial aid related to study abroad. Note that supplemental charges and travel should be listed by the student in their financial-aid budget so that these amounts can be considered when funding is calculated.

Additional information including application procedures and exact deadline dates is available from the Fellowships Advising and Study Abroad Office at http://www.fasa.caltech.edu.

Cambridge Scholars Program

The Caltech Cambridge Scholars Program offers qualified juniors and seniors the opportunity to spend a fall or winter term at the University of Cambridge in England. Students are hosted by and live in one of the Cambridge Colleges participating in the program. The participating colleges are Corpus Christi, Pembroke, St. Catharine's, and St. John's. Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for room and tuition. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one Cambridge department in the biological sciences, physical sciences, computer sciences, mathematics, engineering, or economics to take classes within the tripos, i.e., subject, offered by that department. Students may only take courses in one subject area, unless special permission is granted, and this is usually granted by Cambridge if a student needs a course to fulfill a Caltech option requirement. Students will find more information on the tripos structure and Cambridge University in the Fellowships Advising and Study Abroad Office or at http://www.cam.ac.uk.

During the term at Cambridge, students take the equivalent of at least 36 Caltech units, usually four Cambridge courses, but may take five in most cases. The exact number of courses depends on Cambridge departmental requirements. For their classes, students receive a minimum of 36 Caltech units that can be used for general or option credit. 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 3.2 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.

Copenhagen Scholars Program

The Caltech Copenhagen Scholars Program offers qualified juniors and seniors the opportunity to spend the fall at the University of Copenhagen (KU) or the Danish Technical University (DTU). At KU students may concentrate in the physical sciences, mathematics, biological sciences, or economics. At DTU students can take courses in engineering or the applied sciences as well as the sciences—chemistry, physics, and math, among others, are also taught at DTU.

Students live in a modern dormitory with Danish students. There is a supplemental charge for the room because the Copenhagen semester is 15 weeks long plus one week of fall vacation. The supplement varies yearly depending on prices and the exchange rate.

There is no board plan, but each hall has a well-equipped kitchen, and students may cook for themselves or with the other students. Aside from 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, each student participating in this program is given the board fee in the form of a check, to spend on food while in Copenhagen. Caltech fees are due by the normal fall due date.

Both KU and DTU are on a semester system, and Caltech students attend from around August 25 to mid-December. Students have a one-week vacation in mid-October, and many use this vacation week to travel in Denmark or Europe. DTU students attend a one-week orientation the last week of August, and students going to KU have an advice and orientation period the last week of August.

Students take two to four courses in their Caltech option or a closely related subject and a course in the Danish language. Students attending Copenhagen University are required to take the course in Danish culture, but may substitute or take in addition a course taught in English on subjects such as the Danish monarchy, Danish architecture, Danish film, or the Vikings, depending on what is offered that fall. Students who will be studying primarily at DTU are required to take the Danish-language course and may audit or take for credit a course in Danish culture or take one of the courses noted above. The Danish-culture course, in addition to weekly lectures, offers field trips to interesting cultural and historical sites in the city and surrounding area. All upper-level undergraduate or beginning graduate level courses at KU and DTU can be taught in English. More information can be found at http://www.dtu.dk or http://www.ku.dk.

For this work, students receive a minimum of 36 Caltech units that can be used for general or option 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 can enroll in an optional three-week-long Danish-language course that is given the first three weeks of August. There is no charge for this course. The course is not required.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors should apply by the January deadline for the fall semester at KU or DTU.

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 term can only be attended in years that do not overlap with Caltech term dates and only with the permission of École Polytechnique and Caltech. In addition, seniors may not attend the spring term if they plan to graduate in June.

The École Polytechnique (the "Polytechnic School"), often referred to by the nickname X, is the foremost French grande école of engineering (according to French and international rankings). Founded in 1794 and initially located in the Latin Quarter in central Paris, it was moved to Palaiseau in 1976. It is one of the oldest and most prestigious engineering schools in the world, with a very selective entrance exam. As one of the world's foremost establishments in science education, the École Polytechnique trains graduates who become outstanding scientists, engineers, researchers, managers, and politicians.

At École Polytechnique students can take courses in engineering or the applied sciences as well as the sciences—chemistry, physics, and math, among others, are also taught at École Polytechnique. Students can also take classes in the social sciences and humanities. Two classes must be in the student's Caltech option in science, engineering, or economics and two classes can be taken in other subjects or in the student's option.

All classes are taught in French and all discussions, assignments, and exams are in French. Students must have very good ability in speaking, reading, and writing French before applying for this program. Students will continue to take French at their level while at École Polytechnique.

École Polytechnique has different academic schedules depending on the year of study. Caltech students who study at École Polytechnique for a term (usually the fall) during their junior or senior year can only select classes from the third year of the École Polytechnique curriculum, and all classes must be selected from this year's curriculum. Note that the second-year classes are not allowed as this year goes from the fall through January and then has a second semester versus two terms. The third-year specialized curriculum has a schedule that corresponds closely to Caltech's three-term system. For further information, go to http://www.polytechnique.edu/page.php?MID=216.

A minimum 3.5 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 a Caltech Study Abroad Proposal and Forms, and complete the École Polytechnique application forms as well as undergoing a formal assessment in French skills by Caltech's French instructor.

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, which are a short walk from George Square (humanities and social sciences) and the King's Buildings (the science and engineering campus).

Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for housing due to the longer length of the term. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one of Edinburgh's academic departments in the College of Science and Engineering. Note that students cannot be admitted into the economics department, but can take 20 credits in that department. Students whose option is BEM or economics may be allowed upon request to take 40 credits in economics in order to fulfill the BEM or economics option requirements.

Students take a minimum of 60 Edinburgh credits per semester and a maximum of 80 credits, but no more than five courses. Students will take a minimum of 40 credits in their option or another science or engineering subject and can take 20 credits (one course) in the College of Humanities and Social Sciences. Note that 60 credits is the standard courseload, but most Caltech students take 70 to 80 credits. Note that at least 36 Caltech units must be taken.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors should apply by the January deadline for the fall semester at Edinburgh.

London Scholars Program

The Caltech London Scholars Program offers qualified juniors and seniors the opportunity to spend the fall at University College London, which is located in the lovely Bloomsbury area of London. University College London (UCL) is on a semester system, and Caltech students attend UCL's autumn semester from about the third week of September to mid-December. All students are required to attend an orientation (Wednesday evening through Friday/Saturday) before classes start. All students live in a UCL dormitory, which is located within a short walk of the academic buildings of the Bloomsbury campus. Students pay Caltech room, board, tuition, and other standard Caltech fees for the term. There is a supplemental charge for housing/board due to the longer length of the term. The supplement varies yearly depending on prices and the exchange rate.

Students are admitted into one of UCL's academic departments in the physical, life, or engineering sciences. Note that students cannot be admitted into the economics department, but can be admitted into the statistical sciences department, which offers many economics courses. Note that students can take up to two courses in the economics department.

Students take two courses in their admitting department. Usually the admitting department is in a subject area that best corresponds to the student's Caltech option, but there is some leeway in this provided the student has the background to be admitted. Note that students can be admitted to two departments and take one course in each if there is a compelling reason, e.g., a dual option or the need to fulfill a course requirement.

An additional two to three courses can be taken in departments other than the admitting department. A typical UCL semester class is 7.5 ECTS course units. Caltech students must take a minimum load of 30 ECTS credits during their semester at UCL and a maximum of 37.5 units. This would be equivalent to 36 to 45 Caltech units. UCL classes can be used for general or option credit. Note that the final number of units and whether the units can be used to fulfill departmental requirements will be determined after faculty review upon a student's return to Caltech.

A minimum 3.0 GPA is required to apply. Eligible sophomores and juniors should apply by the January deadline for the fall semester at UCL.

ROTC

Air Force Reserve Officer Training Corps (AFROTC) offers two-, 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 and graduate 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 one- to four-year scholarships valued at up to 100 percent of annual tuition, along with a nontaxable monthly stipend. Air Force ROTC is offered on the campuses of the University of Southern California, California State University San Bernardino, Harvey Mudd College, Loyola Marymount University, and 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 (213) 740-2670 or visit http://www.usc.edu/afrotc. No military commitment is incurred until entering the junior year of the program or receipt of a scholarship after the freshman year.

The Army ROTC program at USC offers four-, three-, and two-year scholarships that pay tuition costs up to $17,000 a year. In addition, the program pays all contracted cadets a stipend of $2,500 to $4,000 a year and an annual book allowance of another $600. 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 17 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 90098, (213) 740-1850.

Procedures

Students must register on the dates specified in the academic calendar. Students are not registered until they have both

- enrolled in an approved list of courses, *and*
- are current with the Bursar's Office. All undergraduate students with an outstanding Bursar's bill balance of $300 or more and graduate students with a Bursar's bill balance of $1,500 or more will have a hold placed on their registration for the subsequent quarter the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Any student who has not completed both phases of registration within one week after the first day of classes will be removed from the Institute rolls.

Students are required to maintain continuity of registration until the requirements for the Bachelor of Science degree are fulfilled, except in the case of an approved undergraduate student sabbatical. If continuity is broken by withdrawal, reinstatement is required before academic work may be resumed.

Changes in Registration

All changes in registration must be reported to the Registrar's Office by the student prior to the published deadlines. A grade of F will be given in any course for which a student registers and which he or she does not either complete satisfactorily or drop. A course is considered dropped when a drop card is completed and returned to the Registrar's Office. A student may not at any time withdraw from a course that is required for graduation in his or her option, without permission of the registrar.

A student may not add a course after the last day for adding courses, or withdraw from a course after the last date for dropping courses, without the approval of the Undergraduate Academic Standards and Honors (UASH) Committee. Registration for added courses is complete when an add card, signed by the instructor and the student's adviser, has been filed in the Registrar's Office. No credit will be given for a course for which a student has not properly registered. The responsibility for submitting drop cards and add cards to the Registrar's Office before the deadlines for dropping or adding courses each term rests entirely with the student. Failure to fulfill the responsibility because of oversight or ignorance is not sufficient grounds to petition for permission to drop or add courses after the deadline. It is the policy of the UASH Committee that no petitions for the retroactive dropping or adding of courses will be considered except under very extenuating circumstances.

Humanities Drop Policy
Students who do not attend the first class of the term will be automatically dropped from the class. Students who notify the instructor in advance of their inability to attend the first class may remain enrolled in the class at the instructor's discretion.

Summer Research or Summer Reading

Qualified undergraduate students who are regular students at the Institute are permitted to engage in research or reading during the summer, but in order to receive academic credit the student must have the approval of his or her division and must complete the registration process for such summer work before June 1. An undergraduate may not receive payment for research carried out for academic credit. Students who are registered for summer research or reading will not be required to pay tuition for the units. A student may apply up to 18 units of summer research per summer and 36 units in total toward Institute graduation requirements.

The Institute recognizes that students may want to take advantage of paid internships that provide unique off-campus educational opportunities that integrate and enhance the classroom experience. Students are encouraged to explore and discuss such opportunities with their academic adviser and the dean or associate dean of students. If appropriate, the adviser and dean or associate dean can approve such internships as integral to a Caltech educational experience. There is no academic credit for such work. The internships should commence after the end of the third term and end prior to the resumption of classes in the fall.

Undergraduate Student Sabbatical

An undergraduate student sabbatical must be sought by written petition, which must be accompanied by a completed withdrawal card. The dean or associate dean of students may grant a sabbatical provided (a) the student is in good standing, in other words does not have to meet special academic requirements as a result of reinstatement, (b) the sabbatical is for one year or less, although special circumstances can be considered, and (c) the sabbatical extends over a period that includes at least one full term.

The dean or associate dean may also grant a leave for medical reasons provided the petition is recommended by the senior director of health and counseling services. Return from a leave for medical reasons also requires the recommendation of the senior director of health and counseling services, and the final approval of the dean or the associate dean. A student returning from a leave for medical reasons will maintain the same academic standing that he or she had previously.

Involuntary Leave
The dean of students may place a student on an involuntary leave if persuaded by the evidence that such action is necessary for the protection of the Institute community or for the personal safety or welfare of the student involved. The withdrawal card may state a specific date after which the student may return or it may be indefinite as to term. The dean of students may stipulate conditions that must be met before the student may return. These conditions might include a letter of recommendation from the senior director of health and counseling services. A decision by the dean to place a student on involuntary leave is subject to automatic review within seven days by the vice president for student affairs (or his or her designee).

Withdrawal from the Institute

Formal separation from the Institute is effected by filing a completed withdrawal card in the Dean of Students Office to be forwarded to the registrar and other appropriate offices. The effective date of a withdrawal is entered by the dean or associate dean of students. A student leaving the Institute at any time during the term without filing a formal withdrawal card will not be considered withdrawn. In such a case, any grades reported by the instructors will be recorded on the official transcript, and the grade of F will be recorded for all other courses. A student who withdraws, or is absent for a term (or longer), without an approved undergraduate student sabbatical, must petition for reinstatement to return to the Institute. Return from involuntary leave requires approval through the Dean of Students Office. Reinstatement rules are listed under scholastic requirements. If the withdrawal occurs after Add Day of any term, a W (standing for "withdrawn") will be recorded on the student's transcript for all courses in which the student is enrolled. A grade of W is not included in the computation of the student's grade-point average. The record will also indicate whether an undergraduate student sabbatical was granted.

SCHOLASTIC REQUIREMENTS

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

Eligibility for Registration
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. Undergraduates who register for programs that make it appear they are no longer candidates for a B.S. degree or who are not making satisfactory academic progress may be refused further reg-

istration by the Undergraduate Academic Standards and Honors (UASH) Committee.

Freshmen are ineligible to register for subsequent terms

- if they have accumulated 24 or more units of E or F, exclusive of PE;
- if they have accumulated three or more course grades of E or F, exclusive of PE;
- if, in any term of their freshman year following a reinstatement, they obtain six or more units of E or F, exclusive of PE.

Ineligible freshmen must petition the UASH Committee for reinstatement if they wish to continue as students. The dean of students or associate dean may act on a petition if (i) it is the student's first ineligibility and (ii) the student has received fewer than 42 units of E or F, exclusive of PE. For other petitions, action must be taken by the UASH Committee.

Undergraduate students, except first- and second-term freshmen, are ineligible to register for another term

- if they fail during any one term to obtain a grade-point average of at least 1.4, or if they receive 27 or more units of E or F, exclusive of PE, during any one term;
- if they fail to obtain a grade-point average of at least 1.9 for the academic year, or if they accumulate 45 or more units of E or F, exclusive of PE, over the academic year (students who have completed at least three full terms of residence at the Institute and have been registered for their senior year shall no longer be subject to the requirement that they make a grade-point average of at least 1.9 for the academic year—seniors must, however, receive a grade-point average of at least 1.4 or receive fewer than 27 units of E or F each term);
- if they have completed fewer than 36 units in the previous term and fewer than 99 units in the previous three terms in residence;
- if, once reinstated, they fail to complete a full load of at least 36 units in the following term with a grade-point average of at least 1.9.

If a late grade makes a student ineligible after the start of the next term, the official transcript shall show the ineligibility and a reinstatement. If the late grade is reported to the registrar before midterm deficiency notices are due for the subsequent term, the student shall be held to the requirement as above to complete a full load of at least 36 units with a grade-point average of at least 1.9.

If a late grade received on or before the last day for adding classes makes a reinstated student eligible, the ineligibility and the reinstatement will be removed from the student's record.

No student ineligible to register on the first day of classes will be permitted to register unless a petition for reinstatement has been submitted and acted upon.

Students ineligible for registration because of failure to meet the requirements stated in the preceding paragraphs 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.* A second reinstatement by UASH will be granted only under exceptional conditions.

Departmental and Option Regulations

Selection of Option
By the middle of the third term, freshmen must notify the Registrar's Office of their selection of an option in engineering, humanities, social sciences, or science to be pursued in subsequent years. Upon the selection of an option, a freshman will be assigned an adviser in that option, whose approval must then be obtained for registration for the following year.

Undergraduate students may request to add an approved minor to their program of study. The request for a minor must be approved by the option representatives of the student's option and proposed minor. A plan must be presented which meets the minimum requirements for both the option and the minor, but the option representatives may impose additional requirements as well. The approved request must be submitted to the registrar before the start of the senior year. Any changes to the approved program will require approval by both advisers.

Undergraduate students may be allowed to major in two options for the Bachelor of Science degree. In order to do so the student must present a rationale for the double option and a plan of study leading to completion of the degree in four years. The plan, and any substantive modifications, must be approved by a committee composed of the option representatives of the two options. The plan must meet the minimum requirements for both options as set forth in this *Catalog*, but the committee may impose additional requirements as well. The approved plan should be submitted to the registrar during the sophomore year, but in any case no later than the start of the senior year. The student will then be assigned an adviser by each option. Consult the registrar for appropriate procedures.

Continuing in an Option
Students whose grade-point averages are less than 1.9 at the end of an academic year in a specific group of subjects designated by their department or option may, at the discretion of their department,

be refused permission to continue the work of that option. Such disbarment does not prevent the students from continuing in some other option or from taking additional courses to raise their average in their original option. Students without an option will fall under the direct jurisdiction of the dean of students. Students may remain without an option for no more than one year.

Change of Option

An undergraduate in good standing at the Institute shall be permitted to transfer into any option of his or her choice provided he or she has (a) a 1.9 GPA in subjects required for graduation in that option or in a specific group of subjects designated by that option or (b) permission of the option representative or committee.
A change of option is effected by obtaining a Change of Option petition from the Registrar's Office. The completed petition must then be signed by the option representative for the new option (who will assign a new adviser), and filed with the Registrar's Office. Institute regulations require that a student who has made normal progress at the Institute be able to change options at any time up to the end of the sophomore year without penalty either as to time until graduation or as to excessive unit requirements in any term.

Term Examinations

Term examinations will be held in all subjects unless the instructor in charge of any subject shall arrange otherwise. No student will be exempt from these examinations. When conflicts exist in a student's schedule, it is the student's responsibility to report the conflict to the instructor in charge of one of the conflicting examinations and make arrangements for another time.

Satisfactory Academic Progress

A student will be declared ineligible to register if he or she has completed fewer than 36 units in the previous term and has completed fewer than 99 units in his or her three most recent terms in residence.

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.

Candidacy for the Bachelor's Degree

A student must file with the registrar a declaration of candidacy for the degree of Bachelor of Science on or before the first Monday of November preceding the date on which he or she expects to receive the degree. All subjects required for graduation, with the exception of those for which the candidate is registered during the last term of his or her study, must be completed and the grade recorded, by the second Monday of May preceding commencement.

Graduation in the Normally Prescribed Time
Any undergraduate student who fails to complete the requirements for graduation at the end of 12 terms must petition the Undergraduate Academic Standards and Honors Committee for approval to register for further work each term.

Requirement for a Second Bachelor of Science Degree
Under exceptional circumstances a student may be permitted to return to study for a second Bachelor of Science degree. To receive this permission the student must petition the Curriculum Committee. If the petition is approved, the student must then register for three consecutive terms of additional study, completing in each term at least 36 units, and must meet all the requirements for graduation in the second option. If additional time is needed to complete the degree, the student must also petition the Undergraduate Academic Standards and Honors Committee for an extension. A student admitted for a second Bachelor of Science degree in a particular option may not change to another option without first submitting a new petition to the Curriculum Committee and receiving the explicit approval of that committee.

Graduation with Honor
Students who have achieved a high scholastic standing or who have carried out creative research of high quality may be recommended to the faculty for graduation with honor by the Undergraduate Academic Standards and Honors Committee. The Committee shall consider for graduation with honor those students who have achieved an overall grade-point average of 3.5 and others who, on the basis of exceptional creativity, have been recommended to the Committee by a faculty member or by a division of the Institute.

Excess of or Fewer Than Normal Units (Overloads and Underloads)
An overload is defined as registration for more than 54 units by an upperclassman or more than 51 units by a freshman. An underload is registration for fewer than 36 units. A student who wishes to carry an overload in any term must obtain the approval of his or her adviser and of the dean or associate dean of students. Petitions for overloads will not be accepted later than the last day for adding classes in any term.

Underloads for freshmen, sophomores, and juniors must be approved by the dean or associate dean. Seniors may take an underload by presenting for the registrar's approval a senior underload petition and a course plan for graduation the following June, provided that the plan does not require an overload in any term.

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 have a copy of the transcript of their work sent to the Registrar's Office. The student should then obtain an Allowance of Credit form from the Registrar's Office and take this, with the transcript, to the representative of the option in which credit is desired. Credit will be granted when this form, with the appropriate signatures, is returned to the office.

Allowance of Credit in the Humanities and Social Sciences
In general, Caltech students should fulfill Caltech course requirements by taking courses at Caltech. Students are expected to have a well-reasoned educational goal for taking classes elsewhere. The only exceptions are transfer students admitted to advanced standing. Credit for comparable work done at other institutions with similar academic standards is not granted automatically.

Students who wish to take courses elsewhere (whether on leave, in the summer, or during the academic year) should consult, *in advance*, with the executive officer for the humanities or the executive officer for the social sciences, or their designees, to minimize any misunderstanding regarding the nature of credit they may receive. Upon completion of the course, the student must obtain an Allowance of Credit form from the registrar, obtain the signed approval of the executive officer, or his or her designee, for transfer credit, and return the completed form to the Registrar's Office. The executive officers are the final authority in the allowance of credit.

Guidelines and specific information about allowance of credit are available from the Division of the Humanities and Social Sciences.

Other Allowances of Credit
Except for transfer credit and credit based on Caltech placement exams upon admission, credit will not be granted for Caltech courses in which the student is not officially enrolled, except in special circumstances by arrangement with the instructor. Such arrangements must be approved by the Curriculum Committee, and the student must petition the Committee before the work is undertaken.

UNDERGRADUATE EXPENSES

For freshman and transfer students applying for admission, there is a $60 application fee. This fee is nonrefundable.

Housing contracts must be submitted to the assistant director of housing-occupancy by the date specified in the instructions accompanying the contract.

Expense Summary 2009–10

General:

General Deposit	$ 100.00[1]
Orientation Fee	500.00[1]
Tuition	33,324.00
	$ 33,924.00

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

Other:

Student Fees	$ 1,260.00
Room (contract price)	6,078.00
Board (5 days/week)	4,677.00
Additional Meal Allowance (est.)	1,413.00
Books and Supplies (est.)	1,290.00
Personal Expenses (est.)	1,926.00

The tuition and fees charge for all students is payable in three installments at the beginning of each term. Fees are subject to change at the discretion of the Institute.

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. These prorated charges will be compared to the payments received on behalf of the student, and the Institute will determine whether the student is entitled to a refund or owes additional funds to Caltech.

For students receiving funds from federal Title IV, from Caltech, and/or from state programs, the Institute will follow federal and other applicable regulations to determine the amount of all program funds the student has earned at the time of withdrawal. In general, the amount of financial aid earned is based on the amount of time the student has spent in academic attendance. If the amount of aid disbursed to the student is greater than the amount the student has earned, unearned funds must be returned. If the amount the student was disbursed is less than the amount the student earned, the student will be eligible to receive a postwithdrawal disbursement.

The Department of Education has provided a summary of these regulations in the Student Guide for the 2009–10 award year, available online at http://studentaid.ed.gov/students/attachments/siteresources/FundingEduBeyondHighSchool_0910.pdf.

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 prior to the first day of classes for the period of enrollment, Caltech will return 100 percent of the student's federal financial aid in accordance with federal procedures, as well as Caltech and/or state grants or aid.

If a student withdraws any time after the first day of classes for the period of enrollment, the Institute will perform the following:

- Determine the percentage of the payment period that the student completed. If the student completed more than 60 percent of the period, he or she earned 100 percent of the aid for the period. If the student completed 60 percent or less, the percentage of the period completed is the percentage of aid earned. This percentage is determined by dividing the number of days attended in the period of enrollment by the total days in the period.
- Apply the earned percentage to the amount of aid actually disbursed and the amount that could have been disbursed ("earned aid").
- Subtract earned aid from aid that was actually disbursed. This results in the amount of unearned aid to be returned.

The Financial Aid Office and/or the Graduate Office (as appropriate) will allocate the return of funds back to the student aid programs in the following order:

1. Federal Direct Unsubsidized Stafford Loan Program
2. Federal Direct Subsidized Stafford Loan Program
3. Federal Perkins Loan Program
4. Federal Direct PLUS Loan Program
5. Federal Pell Grant Program
6. Federal SEOG Program
7. Other Title IV Programs

Any remaining refund will be returned to the other state, institutional, or private student assistance utilized. Federal Work Study is not included in any of these calculations.

Appeals on Refunds: Any questions or problems related to refunds should be directed to the Bursar's Office. For further information on refunds and repayments, contact the Financial Aid Office, the Graduate Office, or the Bursar's Office.

Dropping a Course: A student's financial-aid package will be adjusted to reflect any tuition adjustment made by the Bursar's Office as well as any other adjustments required by law or by the applicable fund donor(s). In addition, 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.

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 148.

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 refunded.

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. A $50 late penalty will be charged by the Bursar's Office for failure to clear a past-due account within five days of the beginning of instruction.

Honor System Matters

Monies owed to the Institute resulting from a Board of Control decision may be collected through the Bursar's Office, at the request of the dean of students.

Special Fees
Students taking the Summer Field Geology course (Ge 120 ab) should consult with the division about travel and subsistence arrangements and costs.

Unpaid Bills
All bills owed the Institute must be paid when due. Any student whose bills are past due may be refused registration for the following term. All undergraduate students with an outstanding bursar's bill balance of $300 or more will have a hold placed on their registration for the subsequent quarter the day before online registration opens. The hold will be released once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Caltech Credit Card Charges
If an undergraduate student owes more than $300 at the end of the quarter, the student's ID card will be deactivated on the seventh day of the following quarter and they will be unable to charge any new purchases. Cards will be reactivated once students have paid their bill or worked out a satisfactory payment plan with 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, see pages 165–174.)

All students who believe they will need assistance to attend Caltech are encouraged to submit financial-aid applications.

The Financial Aid 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 110-87, Pasadena, CA 91125, call (626) 395-6280, or visit the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

How to Apply for Financial Aid

Slightly different procedures and deadlines exist for each category of students applying for financial aid. Detailed descriptions of these procedures and priority due dates for prospective and continuing students may be found on the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

Application Process for Caltech and Federal Financial Aid for Entering Students (U.S. citizens and eligible noncitizens)

The following materials are needed to apply for all financial-aid funds administered by the Caltech Financial Aid Office. We realize that you may not have access to your completed 2009 federal income-tax information by the priority due dates and ask that you complete the application based on the best estimates available.

CSS/Financial-Aid PROFILE Application:

Register for the 2010–11 CSS/Financial Aid PROFILE after October 1, 2009. Designate "California Institute of Technology" as one of the recipients by using Caltech's CSS Code 4034. Due Dates: Applicants must register for the CSS/Financial Aid PROFILE by December 15, 2009. Regular Decision applicants must submit the completed PROFILE application by January 15, 2010. Note: Early Action applicants must register for the CSS/Financial

Aid PROFILE by October 15, 2009, and must submit the completed PROFILE application by November 15, 2009.

Free Application for Federal Student Aid (FAFSA):
The 2010–11 FAFSA will be available on January 1, 2010, at www.fafsa.ed.gov. File the FAFSA and designate "California Institute of Technology" as the recipient by using Caltech's Undergraduate Federal Code Number 001131. Due date: February 1, 2010.

Parents' and Students' Federal Income Tax Return:
Parents and students must submit 2009 Federal Income Tax Returns (including all schedules and W-2s) before eligibility for financial aid can be determined. Applicants will be sent an e-mail from the College Board with instructions on how to submit their tax returns using the Institutional Documentation Service (IDOC). Log in to the IDOC site at https://idoc.collegeboard.com/idoc/index.jsp, download and complete the IDOC cover sheet, and submit your 2009 federal income-tax return, all schedules, all W-2 forms, and all other required documents directly to the College Board. If you or your parents own corporations, partnerships, or trusts, please include copies of those tax returns (Forms 1041, 1065, 1120, 1120S, K-1). If you or your parent(s) did not and will not file a federal income tax return, please complete the Parent or Student Certification of Nonfiling. Please attach copies of W-2 or 1099 forms (if applicable) to the Parent or Student Certification of Nonfiling. Use the IDOC Cover Sheet to submit this form and all other required documents directly to the College Board along with your IDOC cover sheet. Due date: March 2, 2010.

Verification Worksheet:
All students and parents must complete and sign the 2010–11 Verification Worksheet, available at www.finaid.caltech.edu/forms. Use the IDOC cover sheet to submit the appropriate worksheet directly to the College Board. Due date: March 2, 2010.

Caltech Supplemental Application:
All students must complete the 2010–11 Caltech Supplemental Application, available at www.finaid.caltech.edu/forms. Use the IDOC cover sheet to submit this form directly to the College Board. Due date: March 2, 2010.

CSS Noncustodial PROFILE Application:
If your parents are divorced, separated, or never married, your noncustodial parent will need to complete the 2010–11 CSS Noncustodial PROFILE Application. After your CSS/Financial Aid PROFILE application is processed, you will receive an e-mail from the College Board with instructions on how to submit this information. Once you have your login information your non-

custodial parent can access the application at https://ncprofile.collegeboard.com/ncpWeb/pageflows/Main/Ncp MainController.jpf. Due date: March 2, 2010.

CSS Business/Farm Supplement:
If you or either of your parents is self-employed or owns a business or farm, you will need to submit the 2010–11 CSS Business/Farm Supplement, available at the Caltech Financial Aid Office Website. You will receive an e-mail from the College Board with instructions on how to submit this form and other required tax documents using the Institutional Documentation Service (IDOC). Log in to the IDOC site to get your IDOC cover sheet. Use the IDOC cover sheet to submit this form and all other required documents directly to the College Board. Due date: March 2, 2010.

Caltech Scholarship Data Form:
Complete the 2010–11 Caltech Scholarship Data Form to be considered for named and endowed scholarships. Entering students will not be issued a Caltech ID number—required for the form—until sometime in June 2010. Due date: July 15, 2010.

International Applicants
If you are applying for admission as a freshman for the fall of 2010 and are not a citizen or permanent resident of the United States at the time of your application for admission, you will need to refer to the Caltech Financial Aid Office website at http://www.finaid.caltech.edu for instructions for applying for financial aid. International applicants who do not apply for financial aid by published deadlines, or who are denied aid for their first year at Caltech, are not eligible for need-based financial aid for any other academic period while they are undergraduates at the Institute (with the exception of citizens of Canada and Mexico). Those with financial-aid offers will be eligible to apply for assistance in subsequent years. All eligible students must reapply for aid each year.

Starting with the 2010–11 academic year, international students will be 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, 2009, 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, 2010. Please refer to the complete application instructions provided on the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

Types of Aid Available

There are three basic categories of financial aid that may be awarded.

1. Grants and scholarships represent "gift aid," which does not need to be repaid. In general, a Caltech Scholarship is awarded based on financial need. Caltech named and/or endowed scholarships are considered to be based on need and merit, with the exception of the Lingle, Axline, and President's Scholarships, which are based only on 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 we have students interested in working.
3. Low-interest educational loans: Students are generally offered Federal Perkins Loans or Caltech/Institute Loans. Students may be awarded Federal Direct Stafford Loans if they request them.

Caltech Scholarships

Awarded to students with demonstrated financial need. Recipients are expected to be enrolled full time. The named and/or endowed scholarships are also need-based but many have a merit component. Recipients of named and/or endowed scholarships are often selected after their initial financial-aid offer based on scholarship-specific eligibility. These scholarships are almost always used to replace some or all of the recipient's Caltech scholarship. The Financial Aid Office makes every attempt to renew these scholarships, contingent upon the recipients continuing to meet the specific eligibility criteria.

Federal Grants

Federal Pell Grant

Awarded to exceptionally needy undergraduate students who are seeking their first bachelor's degree. Amounts are set by the federal government based on need and enrollment status. In 2009–10, awards ranged from $976 to $5,350 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.

Academic Competitiveness Grant
Awards $750 for the first year of undergraduate study and $1,300 for the second year of undergraduate study to students who are enrolled at least half-time, are receiving a Federal Pell Grant, are U.S. citizens or eligible noncitizens, and have completed a rigorous high-school program as determined by the state or local education agency and the U.S. Secretary or Education. (For the published list of rigorous programs of study, go to http://www.ed.gov/admins/finaid/about/ac-smart/state-programs.html.) Second-year students must have maintained a cumulative grade point average of at least 3.0 on a 4.0 scale.

National SMART Grant
Awards $4,000 for the third and fourth years of undergraduate study to students who are enrolled at least half-time, are receiving a Federal Pell Grant, are U.S. citizens or eligible noncitizens, and have a cumulative grade point average of at least 3.0 on a 4.0 scale in the courses for their program (not only those in the major); and are majoring in physical, life or computer science, engineering, mathematics, technology, or a critical foreign language.

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 $9,708, 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 averages 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 $1,551 for books and living expenses. When renewed or applied beyond the first year, awards also include tuition and fee assistance of up to $9,708. 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 at attend Caltech. Students are encouraged to contact their respective state post-secondary agencies for specific eligibility and renewal criteria.

Educational Loans

An educational loan is a serious financial obligation and must be repaid. You should carefully consider the repayment obligation before you accept educational loans. Loans can be an invaluable resource for many students and their families in financing a college education. Students can postpone paying a portion of their educational costs until they complete their education or leave school. The repayment period on most loans can extend up to 10 years after graduation or leaving school.

Graduating with educational debt is a fairly common experience for students. At Caltech, however, the average educational indebtedness at graduation is significantly lower than the national average for students attending four-year private and public colleges. Over the last several years, the average for Caltech graduates has been among the lowest in the nation for four-year colleges.

Federal Perkins Loans
Awarded to students based on financial need. The maximum amount an eligible student may borrow is $5,500 per award year if he or she has not successfully completed a program of undergraduate education ($8,000 per year for graduate students). The maximum aggregate amount that may be borrowed is $11,000 for any student who has not yet completed two years of undergraduate work; $27,500 for an undergraduate student who has completed two years of undergraduate work and is pursuing an undergraduate degree; and $60,000 for a graduate student, including loans borrowed as an undergraduate. The aggregate loan limits include only the unpaid principle. Perkins Loans carry an annual interest rate of 5 percent. Interest does not accrue while the borrower is enrolled in school at least half-time, during the grace period (the time before which the borrower must begin or resume repaying a loan), or during authorized deferments. The borrower is responsible for paying the interest that accrues on the loan during repayment or forbearance (a temporary postponement of payments). Loans are repayable over a period of up to 10 years and have a nine-month initial grace period.

Your monthly payment amount will depend on the size of your debt and the length of your repayment period. The minimum monthly payment is $40.

The William D. Ford Federal Direct Loan Program
This program offers eligible students and parents the opportunity to borrow money directly from the federal government to help

pay the cost of attendance at Caltech. The U.S. Department of Education makes loans, through Caltech, directly to students and/or parents. The Institute will use the loan(s) to pay your tuition/fees and other direct charges such as room and board, and give the student any remaining money for indirect costs. Students and/or parents make their repayments directly to the federal government.

Direct Loans include

1. The Federal Direct Stafford Loan Program;
2. The Federal Direct Parent PLUS Loan Program;
3. The Federal Direct Graduate PLUS Loan Program; and
4. The Federal Direct Consolidation Loan Program.

Federal Direct Stafford Loan

There are two types of Federal Direct Stafford Loans: subsidized and unsubsidized. The federal government pays the interest on subsidized loans while the borrower is enrolled at least half-time and during authorized periods of deferment. The interest on unsubsidized loans begins to accrue immediately upon disbursement and is generally capitalized (added to the amount borrowed) when the borrower is no longer enrolled at least half-time.

Eligibility for subsidized Stafford Loans is based on financial need as demonstrated by the FAFSA. Students who do not demonstrate sufficient need or whose need is met may borrow unsubsidized Stafford Loans provided their total financial aid, including the Stafford Loan, does not exceed the total estimated cost of attendance.

Dependent undergraduate students (excluding students whose parents cannot borrow Parent PLUS Loans) may borrow Stafford Loan amounts not to exceed an annual total of

- $5,500 for first-year students, with no more than $3,500 in subsidized Stafford;
- $6,500 for second-year students, with no more than $4,500 in subsidized Stafford; and
- $7,500 for third- and fourth-year students, with no more than $5,500 in subsidized Stafford.

Independent undergraduate students and dependent undergraduate students whose parents are unable to borrow Parent PLUS Loans may borrow additional unsubsidized Stafford Loan amounts not to exceed an annual total of

- $9,500 for first-year students, with no more than $3,500 in subsidized Stafford;
- $10,500 for second-year students, with no more than $4,500 in subsidized Stafford; and
- $12,500 for third- and fourth-year students, with no more than $5,500 in subsidized Stafford.

Graduate students may borrow Stafford Loan amounts not to exceed an annual total of $20,500, with no more than $8,500 in subsidized Stafford.

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.

The interest rate on subsidized Stafford Loans disbursed for enrollment periods that begin after July 1, 2009, is fixed at 5.6 percent. The interest rate on subsidized Stafford Loans disbursed for enrollment periods that began after July 1, 2008, is fixed at 6.0 percent. The interest rate on subsidized and unsubsidized Stafford Loans disbursed for enrollment periods that began after July 1, 2006, is fixed at 6.8 percent. The interest rate for loans disbursed for enrollment periods that began before July 1, 2006, is variable and will be adjusted each year on July 1, though it will never exceed 8.25 percent. 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. From July 1, 2009, to June 30, 2010, the origination fee for Stafford Loans is 1.5 percent. The maximum repayment period under this program is 10 years, not including authorized periods of deferment. Direct Stafford Loans have a 6-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 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 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. The interest rate on Parent PLUS loans disbursed for enrollment periods that began after July 1, 2006, is fixed at 7.9 percent. 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 of 4 percent of the principal amount of each Direct Parent PLUS loan received. For Parent PLUS Loans that are first disbursed on or after July 1, 2008, parent borrowers have the option of deferring repayment based on the enrollment status of the dependent student on whose behalf a Direct PLUS Loan was obtained.

Specifically, Parent PLUS Loan borrowers may defer repayment

- While the dependent student on whose behalf the loan was obtained is enrolled on at least a half-time basis, and
- During the six-month period after the dependent student on whose behalf the loan was obtained ceases to be enrolled on at least a half-time basis.

If a Parent PLUS Loan borrower does not request a deferment, the first payment on the loan will be due within 60 days after the loan is fully disbursed.

Applications for Federal Direct Parent PLUS loans are available on the Caltech Financial Aid Office website. Applications must be submitted to the Financial Aid Office for eligibility certification. Complete information on Parent PLUS loan deferments and repayment options is also available from the Financial Aid Office.

Federal Student Aid Ombudsman

The Federal Student Aid Ombudsman works with student loan borrowers to informally resolve loan disputes and problems. The office of the ombudsman helps borrowers having problems with the following federal loans: Direct loans (subsidized and unsubsidized Direct Stafford loans, Direct PLUS loans, and Direct Consolidation loans); Federal Family Education loans (subsidized and unsubsidized Stafford loans, FFEL PLUS loans, and FFEL Consolidation loans); guaranteed student loans, SLS loans, and Federal Perkins loans. If a student needs the assistance of the ombudsman in order to resolve disputes or problems, he or she may contact the office at U.S. Department of Education, FSA Ombudsman, 830 First St., NE, Washington, D.C., 20202-5144; (202) 377-3800 or (877) 557-2575; fsaombudsmanoffice@ed.gov; or visit the website at http://www.ombudsman.ed.gov.

Caltech Loans
Awarded to students who are not eligible for or who may have used their eligibility for Federal Perkins Loans. Generally, no interest is charged and no repayment of principal is required while a student maintains a continuous course of study at Caltech. Like the Federal Perkins Loan program, repayment on Caltech Loans begins nine months after graduation, leaving school, or less than half-time enrollment. Caltech Loans carry an annual interest rate of 5 percent. More specific information is provided on the promissory note and the disclosure statement provided to students prior to disbursement of the loan.

Cecil L. Kilgore Student Loans are available to members of all undergraduate classes, including freshmen, under the same general guidelines established for Caltech Loans as described above. It is the fund's policy to make loans available at the lowest possible cost to the student, with priority given to students in the field of power engineering.

Other Loans/Emergency Loans may be available to students regardless of their eligibility for financial aid. *The Hoover Loan Fund* enables students to borrow small sums of money to cover unforeseen emergencies. 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.

Alternative Loans
Several private organizations offer a variety of long-term loans to assist students and families in meeting college expenses. Information about some of these programs is available upon request from the Caltech Financial Aid Office and on the Caltech Financial Aid Office website at http://www.finaid.caltech.edu.

Student Employment

Work programs provide students with a double incentive—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 http://www.career.caltech.edu/joblistings/index.shtml to register on NACElink to see relevant job listings. Note that students are discouraged from working more than 16 hours per week and must seek the approval of the Dean of Students to do so. First-year students may not work during fall term and must receive the Dean of Students's approval to work during the second or third term. Note that first-year students are usually permitted to work unless they have experienced academic difficulty during the previous term or if the dean determines that work would interfere with satisfactory academic progress.

Students can expect to earn at least the California state minimum wage of $8 per hour. Compensation rates will vary based on the position, a student's skills, and previous work experience. Please note that undergraduate students who serve as teaching assistants may only have one assignment per term of up to 12 hours per week. Any assignments involving greater hours require the approval of the Graduate Dean.

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 $2,000 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 term if they receive permission from the dean of students, we've limited student employment awards for entering students to $750 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 their 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 until May 1, 2010.

Please go to the Work-Study page on the Caltech Financial Aid Office website (http://www.finaid.caltech.edu/workstudy) for additional information about student employment at Caltech.

Caltech Work-Study

The Caltech Work-Study Program is funded by the Institute and is designed to provide part-time employment for international students who have demonstrated financial need, and other students who do not qualify for the Federal Work-Study Program. The Caltech Work-Study program is limited to on-campus employment or student employment positions at the Jet Propulsion Laboratory. The program's regulations parallel the Federal Work-Study Program's regulations.

Financial Aid When Studying Abroad

Caltech provides student financial aid (in the form of grants, scholarships, and loans) to those undergraduates with demonstrated financial need who desire to participate in the Institute-sponsored Caltech Cambridge Scholars Program, Caltech Copenhagen Scholars Program, Caltech Edinburgh Scholars Program, or Caltech London 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, 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 132.)

Costs include but are not limited to tuition, fees, room, board, additional meals not covered by a board contract, books, supplies, personal expenses, and a standard transportation allowance from the student's home to Caltech. Transportation expenses related to the student's travel between Caltech and the study-abroad institution are the responsibility of the student; financial-aid recipients may be offered interest-free Institute Loans to cover study-abroad travel expenses. Students will have their expected family contribution and financial package calculated in the same manner as other students. Students studying abroad are subject to the standard Caltech policy of a maximum of 12 terms of eligibility for financial aid. Cambridge, Copenhagen, University College London, and University of Edinburgh Scholars candidates must meet all financial-aid priority deadlines and eligibility requirements to receive aid. It is the student's responsibility to ensure that all necessary documents are filed and complete with regard to their application for financial aid. Cambridge, Copenhagen, University College London, and University of Edinburgh Scholars will continue to be considered for available federal, state, and Caltech grant, scholarship, and loan funds. The Fellowships Advising and Study Abroad Office will make the necessary arrangements with the Bursar's Office to ensure that scholars who may be eligible for funds in excess of the direct charges to the Institute receive those funds prior to their departure.

Other Resources

A number of both local and national organizations offer outside scholarships to continuing students throughout the year, some of these regardless of need. The student newspaper, the *California Tech*, announces eligibility criteria for several such scholarships. Those relevant to undergraduate students will also be posted in the Scholarship News section of the Caltech Financial Aid Office website. Such scholarships can also often be found with the help of a search service. We recommend FastWeb (www.fastweb.com); BrokeScholar (www.brokescholar.com); and College Answer (www.collegeanswer.com). (For more information on scholarship services, go to http://www.finaid.org.)

Outside scholarships acquired by students are considered, by federal regulation, to be a resource available during the academic year. Caltech's policy is to use outside scholarships to replace the student employment and/or loan components of the financial-aid package. For entering students, we generally replace student employment first. For continuing students, loans are generally replaced first. Only if the total outside scholarships exceeds the student employment and/or loan that would have been included in your financial-aid package will it be necessary to reduce Caltech scholarship. In general, a student's total financial aid, including outside assistance, cannot exceed their demonstrated financial need. Under no circumstances can a student's total financial aid, including Caltech merit scholarships, 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

- completed and returned your award letter;
- provided all required documents for the aid programs you have been awarded;
- made satisfactory academic progress;
- enrolled in at least the minimum number of credits for the financial-aid programs you have been awarded;
- completed all necessary loan documents and, for first-time Direct Stafford loan borrowers, completed the online Entrance Interview.

If the disbursement of your aid results in a credit balance, any aid awarded in excess of institutional charges will be paid to the student as a refund. Refunds must be requested by the account holder. Requests may be made by e-mail, telephone, or in person at the Bursar's Office. Prior to receiving funds, it may be necessary to fill out and sign a refund form. Refunds can be obtained in cash or by check. A maximum refund of $500 cash per day can be received from the Bursar's Office cashier. Refund checks are requested by the Bursar's Office and issued by Accounts Payable. This usually takes five working days from the day of request.

Outside scholarships are usually disbursed in the form of a check and must be handled according to the sponsor's specifications. If the funds are sent to the Financial Aid Office or the Bursar's Office, they will be credited to your account. Again, if the crediting of any outside scholarship results in a credit balance on your account, you may request that the credit balance be refunded to you. Federal regulations allow Caltech to credit financial-aid funds to your account for payment of tuition, fees, and room and board charges. You must give the Bursar's Office written authorization to keep a credit balance on your account from one term to the next term during the academic year. Federal guidelines prohibit keeping a credit balance from one academic year to the next. If you complete your financial-aid file late in the term, resulting in the late disbursement of your financial-aid funds, you may be subject to late fees assessed by the Bursar's Office.

Cal Grant B stipend payments will be credited to your tuition account unless you contact the Financial Aid Office in person within the first three weeks of the term to make alternate arrangements. Again, if the crediting of any financial aid results in a credit balance on your account, you may request that the credit balance be refunded to you.

In general, loans are disbursed in three installments, one at the beginning each term. For most Caltech students who are enrolled for the full academic year, this means that one-third of their loan(s) will be disbursed at the beginning of the fall term, another at the beginning of the winter term, and the final third at the beginning of the spring term. Students whose loan periods are for one term receive their entire disbursement at the beginning of that term. If you work through either the Federal Work-Study or the Caltech Work-Study program, you will be paid by check through the biweekly Caltech payroll system. Checks are normally distributed at your actual work site.

Since financial aid is generally awarded on the assumption of full-time enrollment, it is possible that some or all of your aid will need to be adjusted if your enrollment status results in a reduction in your tuition for a term. If you withdraw or drop below half-time enrollment after the last day for adding classes for a term, you may be required to repay all or a portion of the aid that has already been credited to your account. You must inform the Financial Aid Office is you take a leave of absence or change your enrollment subsequent to receiving your financial aid. Cal Grant recipients who take a leave of absence are advised to contact the California Student Aid Commission (www.csac.ca.gov) and submit a form to remain eligible for the program.

You have the right to cancel your loan(s) anytime before disbursement and up to 14 days after disbursement.

Satisfactory Academic Progress

In order to continue to receive financial aid at Caltech, students must maintain satisfactory academic progress toward completion of the baccalaureate degree as defined in the *Caltech Catalog*. Whenever this is not maintained, approval for reinstatement by the

Undergraduate Academic Standards and Honors Committee, the registrar, or the dean of students (as described in the *Caltech Catalog*) shall reestablish satisfactory progress for purposes of financial-aid eligibility. In general, assistance is available to eligible students for the first 12 terms of enrollment (or the equivalent for transfer or less than full-time students). Exceptions may be approved after submission of a petition to the Financial Aid Office. Petition forms are available in the Financial Aid Office.

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)
Underloads (undergraduate students taking less than 36 units in a term) must be approved by the registrar or the Undergraduate Academic Standards and Honors Committee. All students planning to carry an underload should contact the Financial Aid Office prior to taking less than a full-time course load.

PRIZES

Robert P. Balles Caltech Mathematics Scholars Award
An annual prize of $1,000 is awarded to the mathematics major entering his or her senior year who has demonstrated the most outstanding performance in mathematics courses completed in the student's first three years at Caltech. The executive officer for mathematics, in consultation with the faculty, determines the recipient. The prize is made possible by a gift from Mr. Robert P. Balles.

Mabel Beckman Prize
The Mabel Beckman Prize is given in memory of Mrs. Beckman's many years of commitment to Caltech's educational and research programs. The prize is awarded to an undergraduate woman who, upon completion of her junior or senior year at Caltech, has achieved academic excellence and demonstrated outstanding leadership skills, a commitment to personal excellence, good character, and a strong interest in the Caltech community. This prize is given at commencement.

Eric Temple Bell Undergraduate Mathematics Research Prize
In 1963 the department of mathematics established an Undergraduate Mathematics Research Prize honoring the memory of Professor Eric Temple Bell, and his long and illustrious career as a research mathematician, teacher, author, and scholar. His writings on the lives and achievements of the great mathematicians continue to inspire many hundreds of students at Caltech and elsewhere.

A prize of $500 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.

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. Five prizes can be awarded annually, a first prize of $500; second prize, $300; and three $200 third prizes.

Richard G. Brewer Prize in Physics
The Richard G. Brewer Prize is awarded to the freshman with the most interesting solutions to the Physics 11 "hurdles," in recognition of demonstrated outstanding intellectual promise and creativity at the very beginning of his or her Caltech education.

The award is a stipend that will support the student for the summer while he or she works on an independent Physics 11 project. This award is made possible by a gift from Dr. Richard

G. Brewer, a Caltech alumnus who received his B.S. degree in chemistry in 1951.

Fritz B. Burns Prize in Geology
This prize is awarded to an undergraduate who has demonstrated both academic excellence and great promise of future contributions in the fields represented by the Division of Geological and Planetary Sciences.

Bonnie Cashin Prize for Imaginative Thinking
This $5,000 prize, established in 1997 by Bonnie Cashin, is awarded each year to the entering freshman who has written the most imaginative essays in the Application for Freshman Admission. The Freshman Admissions Committee will nominate awardees to the vice provost, who will approve the selection. The award may be shared if there is more than one deserving student in a particular year.

Donald S. Clark Memorial Awards
From a fund contributed by the Caltech Alumni Association, annual awards of $1,000 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 Campus Life and Master's Award
Two or more awards, selected by the deans, the assistant vice president for campus life, and the master of student houses, respectively, are presented to undergraduates whose concern for their fellow students has been demonstrated by persistent efforts to improve the quality of undergraduate life and by effective communication with members of the faculty and administration.

Doris Everhart Service Award
The Doris Everhart Service Award is given annually to an undergraduate who has actively supported and willingly worked for organizations that enrich not only student life, but also the campus and/or community as a whole, and who has, in addition, exhibited care and concern for the welfare of students on a personal basis. The award was made possible by Sally V. Ridge and was established to honor Doris Everhart.

Richard P. Feynman Prize in Theoretical Physics
This prize was established through gifts in memory of Richard P. Feynman and the senior class gift of the class of 1989. It is awarded annually to a senior student on the basis of excellence in theoretical physics. The prize consists of a cash award and a copy of the three-volume set *The Feynman Lectures on Physics*.

Haren Lee Fisher Memorial Award in Junior Physics
Mr. and Mrs. Colman Fisher established the Haren Lee Fisher Memorial Award in Junior Physics in memory of their son. The General Electric Foundation also contributed to the fund under the matching plan of their Corporate Alumnus Program. A prize of $350 will be awarded annually to a junior physics major, who is selected by a physics faculty committee as demonstrating the greatest promise of future contributions to physics.

Henry Ford II Scholar Awards
Henry Ford II Scholar Awards are funded under an endowment provided by the Ford Motor Company Fund, a nonprofit organization supported primarily by contributions from the Ford Motor Company. Each award, up to $5,000, will be made annually either to the engineering student with the best academic record at the end of the third year of undergraduate study, or to the engineering student with the best first-year record in the graduate program. The chair of the Division of Engineering and Applied Science names the recipient.

Jack E. Froehlich Memorial Award
The family and friends of the late Jack E. Froehlich, who did his undergraduate and graduate work at Caltech and was later the project manager for Explorer I for the Jet Propulsion Laboratory, established a prize fund that provides an award of $1,000 to a junior in the upper 5 percent of his or her class who shows outstanding promise for a creative professional career. The student is selected by the deans and the Undergraduate Academic Standards and Honors Committee.

George W. and Bernice E. Green Memorial Prize
The George W. and Bernice E. Green Memorial Prize was established in 1963 with contributions given in memory of George W. Green, who for 15 years served on the staff of the Caltech business office and was vice president for business affairs from 1956 to 1962. The prize of $1,200 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.

Lucy Guernsey Service Award
Awarded to one or two students who have provided exceptional service to the Caltech Y and/or the community, are involved with service projects, have demonstrated leadership in community and volunteer service efforts, and who exemplify a spirit of service. Established by the Caltech Y ExComm in honor of Lucy Guernsey, the Y's executive director from 1989 to 1991.

Arie J. Haagen-Smit Memorial Fund
The Arie J. Haagen-Smit Memorial Award was established in 1977 to honor the memory of the pioneering bioorganic chemist who discovered the chemical constituents of smog. Dr. Haagen-Smit was a member of the Caltech faculty for 40 years, and his family and friends have arranged for a prize of $750 to be given at the end of the sophomore or junior year to a student in biology or chemistry who has shown academic promise and who has made recognized contributions to Caltech. The selection is made by a committee of representatives from the biology and chemistry divisions, and the deans.

Frederic W. Hinrichs, Jr., Memorial Award
The Board of Trustees of the California Institute of Technology established the Frederic W. Hinrichs, Jr., Memorial Award in memory of the man who served for more than 20 years as dean and professor at the Institute. In remembrance of his honor, courage, and kindness, the award bearing his name is made annually to the senior who throughout his or her undergraduate years at the Institute has made the greatest contribution to the student body and whose qualities of character, leadership, and responsibility have been outstanding. At the discretion of the deans, more than one award, or none, may be made in any year. This award is given at commencement.

Alexander P. and Adelaide F. Hixon Prize for Writing
The Hixon Prize for Writing was established in 2000 by Alexander P. and Adelaide F. Hixon. The prize will be awarded annually to an undergraduate student for the best composition in a freshman humanities course. The prize is administered by the writing center, and the winner will be chosen by a committee from the Humanities division, with preference given to the paper best illustrating the relationship between the humanities and science and/or engineering.

The George W. Housner Prize for Academic Excellence and Original Research
The George W. Housner prize is given annually to a senior in the upper 20 percent of his or her class who has demonstrated excellence in scholarship and in the preparation of an outstanding piece of original scientific research. The student is selected by the deans and the Undergraduate Academic Standards and Honors Committee. At the discretion of the dean, more than one award may be made in any year. The prize, presented at commencement, consists of a cash award and a certificate. This prize is made possible by a gift from George W. Housner, Carl F Braun Professor of Engineering, Emeritus.

Bibi Jentoft-Nilsen Memorial Award
Family and friends of Bibi Jentoft-Nilsen, class of 1989, have provided this award in her memory. The cash award of $500 is for an upperclass student who exhibits outstanding qualities of leadership and who actively contributes to the quality of student life at Caltech.

Scott Russell Johnson Undergraduate Mathematics Prize
This prize of $2000 is awarded to the best graduating mathematics major. The prize may be split between two students. In deciding on the winner, special consideration will be given to independent research done as a senior thesis or SURF project. The executive officer for mathematics, in consultation with the faculty, determines the recipient. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. '83.

D. S. Kothari Prize in Physics
This prize was established in 1998 in memory of Dr. D. S. Kothari, who received his Ph.D. under Lord Rutherford in 1933, and subsequently made significant contributions in theoretical astrophysics and science education. The award of $500 is given each year to a graduating senior in physics who has produced an outstanding research project during the past year.

Margie Lauritsen Leighton Prize
From a fund established by Dr. Fay Ajzenberg-Selove and Dr. Walter Selove, the departments of physics and astrophysics will annually award the Margie Lauritsen Leighton Prize to one or two undergraduate women who are majoring in physics or astrophysics, and who have demonstrated academic excellence. The prize consists of a cash award and will be made at the end of the sophomore year.

Harry Leiter Memorial Mechanical Engineering Prize
This prize shall be awarded to a candidate for the degree of Bachelor of Science in mechanical engineering who has demonstrated extraordinary 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. This prize is made possible by a gift from Dr. Symme Leiter.

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.

Dorothy B. and Harrison C. Lingle Scholarship
Each year, the Freshman Admissions Committee selects two incoming freshmen for an annual merit award. The combination of the Lingle Scholarship and any other financial assistance cannot exceed the recipients' estimated cost of attendance. The Lingle Scholarship is awarded in recognition of interest in a career in science or engineering, outstanding academic record, demonstrated fair-mindedness, good work ethic, and unquestioned integrity. The award is renewable for three years, regardless of financial need, contingent upon continuing high academic performance. Such performance is defined as not failing any courses and maintaining honors standing. All admitted freshman applicants will be considered. No special application is required.

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. The prize consists of cash awards amounting to $750.

Galina D. Moller Memorial Fund for Women
The Galina D. Moller Memorial Fund was established to honor Dr. Galina Moller (M.S. '74, Ph.D. '80), an alumna who was keenly aware of the special challenges encountered by professional women. The fund provides support for activities related to study, research, or professional development of undergraduate women. For example, the funds could help defray the cost of attending a conference or seminar. The deans will allocate the funds as appropriate.

Robert L. Noland Leadership Award
The Robert L. Noland Leadership Award is a cash award of $2,000 for upperclass students who exhibit qualities of outstanding leadership. The kind of leadership to be recognized is most often expressed in personal actions that have helped other people and that have inspired others to fulfill their leadership capabilities. The scholarship was set up by Ametek in 1978 in honor of its president, Robert L. Noland, a Caltech alumnus. Two or more awards are generally made each year.

Rodman W. Paul History Prize
The Rodman W. Paul History Prize was established in 1986 by some of his many colleagues and friends to honor Professor Paul's 35 years of teaching and research at the Institute. The prize is awarded annually to a junior or senior who has shown unusual interest in and talent for history.

Doris S. Perpall SURF Speaking Prize
Robert C. Perpall (B.S. '52, M.S. '56) endowed this prize in memory of his late wife, Doris S. Perpall, to encourage students to prepare excellent SURF presentations. SURF Seminar Day is the first round of the Perpall Speaking Competition. The best presentations in each session are nominated for advancement to a second round, held in November. The final round is held in January. Three prizes are awarded annually, a first prize of $500; second prize, $300; third prize, $200.

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. This year the scholarship is worth $6,000.

Richard P. Schuster Memorial Prize
This award is made from a fund 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.

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.

Alan R. Sweezy Economics Prize
The Alan R. Sweezy Economics Prize was established in 1995 by family, friends, and colleagues to honor Professor Sweezy for his 36 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 economics.

Frank Teruggi Memorial Award
The Frank Teruggi Memorial Award was established in 1998 by friends and classmates of the late Frank Teruggi, a Caltech undergraduate who was murdered in Chile in 1973, during the military coup led by Augusto Pinochet.

The annual award of $500 honors the spirit of Frank's life, especially "in the areas of Latin American Studies, radical politics, creative radio programming, and other activities aimed at improving the living conditions of the less fortunate."

Morgan Ward Prize
The Morgan Ward Prize was established by the department of mathematics in 1963 to honor the memory of Professor Morgan Ward in recognition of his long service to mathematics and to the Institute. The competition is open only to freshmen and sophomores. An entry consists of a mathematical problem together with a solution or a significant contribution toward a solution. One or

more winners are selected by a faculty committee acting on the advice of student judges. Each prize of $75 is funded by the same source used to sponsor the Eric Temple Bell Prize.

Fredrick J. Zeigler Memorial Award
The Fredrick J. Zeigler Memorial Award was established in 1989 to honor Fredrick J. Zeigler, a member of the class of 1976 and an applied mathematics major. The award, which carries a cash prize of $2,500, 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; 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 requirements for the B.S. degree are the ones stated in the catalog published in the first year of a student's enrollment at Caltech, under normal circumstances. Changes to those requirements can occur due to actions and decisions made by the student's option, the registrar, the Curriculum Committee, or the Faculty Board. A student may elect to satisfy the requirements stated in a catalog from a different year than that under which the student was registered by first obtaining approval from the Registrar's Office.

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.

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 2009–10 and subsequent years. Some information for continuing students has been provided as footnotes, but guidance on special cases must be sought. Courses used to satisfy core requirements may not be used to satisfy option electives.

Course	*Units*
1. Freshman Mathematics (Ma 1 abc)	27
2. Sophomore Mathematics (Ma 2 ab)	18
3. Freshman Physics (Ph 1 abc)	27
4. Sophomore Physics (Ph 2 ab or Ph 12 abc[1])	18
5. Freshman Chemistry (Ch 1 ab)	15
6. Freshman Biology (Bi 1 or Bi 1 x)[2]	9
7. Menu Class (currently Ay 1, Ch/APh 2, ESE 1, Ge 1, IST 1, or IST 4)	9
8. Freshman Chemistry Laboratory (Ch 3 a)[3]	6
9. Additional Introductory Laboratory	6
10. Scientific Writing[4]	3
11. Humanities Courses (as defined below)	36
12. Social Sciences Courses (as defined below)	36
13. Additional Humanities and Social Sciences Courses	36
14. Physical Education	9

[1] *Students taking Ph 12 a but not Ph 12 c must take one term in Statistical Physics or Thermodynamics from the list: Ph 2 b, APh 17 a, Ch 21 c, Ch 24 b, or ME 18 a.*

[2] *Bi 8 or Bi 9 are acceptable alternatives to Bi 1 or Bi 1 x for students with a strong background in biology. Students who earned a 5 on the AP Biology exam may also petition the biology option representative to take a higher-level biology course of nine or more units to fulfill the biology core requirement.*

[3] *This requirement can also be met by completing Ch 3 b , Ch 3 x, or Ch 4 a.*

[4] *This requirement may be met either by taking a course approved by the student's option to satisfy this requirement, or by taking En 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 (6 units), APh 24 (6 units), Bi 10 (6 units), Ch 3 b (8 units), Ch 4 ab (9 units per term), Ge 116 (6 units), Ph 3 (6 units), Ph 5 (9 units), Ph 8 bc (6 units), or a more advanced laboratory. Computational laboratory courses may not be used to satisfy this requirement.

Humanities and Social Sciences Requirements
All students must complete satisfactorily 108 units in the Division of the Humanities and Social Sciences. Of these, 36 must be in the humanities (art, English, film, history, history and philosophy of science, humanities, music, philosophy, and, with certain restrictions, languages) and 36 in the social sciences (anthropology, business economics and management, economics, law, political science, psychology, social science), in each case divided equally between introductory and advanced courses. The remaining 36 may be drawn from humanities and social sciences, including HSS tutorial courses. They may *not* include reading courses unless credit has been granted by petition to the Humanities or Social Science faculty. In general, no more than 18 units of freshman humanities may be counted toward the 108-unit requirement.

Entering freshmen are required to take two terms of freshman humanities; that is, humanities courses numbered 20 or below in the *Catalog*. These classes introduce students to the basic issues in the three core disciplines of English, history, and philosophy. Successful completion of two terms of freshman humanities is a prerequisite for all humanities courses, except for foreign languages. It is *not* a prerequisite, however, for introductory social sciences. The freshman humanities classes may be taken in any two terms of the freshman year. Other humanities courses numbered 30 or greater are open only to students who have fulfilled the freshman humanities requirement.

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

A student must take 18 units of advanced humanities courses as well. The classes that count as advanced humanities courses are those numbered 90 or above in art history, English, film, history, history and philosophy of science, humanities, language (except for the first four terms of each language), music, and philosophy. With the permission of the executive officer for the humanities, the advanced humanities classes may include any of the foreign language classes beyond the fourth term; students will receive permission except for courses in their native language. The first four terms of a foreign language sequence do not count toward the 36-unit humanities requirement; however, every term receives credit toward the final 36 units of the 108-unit requirement in HSS.

Since writing is a crucial skill, all humanities courses, with the exception of some foreign languages and courses numbered between 29 and 90, require at least 4,000 words of composition. Instructors give extensive feedback on written work and help students improve their prose. As entering students may not be fully prepared for the writing in freshman humanities, all freshmen and transfer students take a writing assessment before the beginning of the fall term. On the basis of this assessment, some students may be required to pass En 1 ab or En 2 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. The introductory social science courses must be drawn from the following list: either An 22 or An 23, Ec 11, Law 33, PS 12, either Psy 15, Psy 16, or Psy 20, SS 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 below.

Introductory Course	*Following Course*
An 22 or 23	advanced anthropology
Ec 11	advanced economics or BEM (except BEM 101)
Law 33	advanced law
PS 12	advanced political science
Psy 15, 16, or 20	advanced psychology
SS 13	advanced economics or political science, or BEM (except BEM 101)

For instance, a student who has taken An 22 and Ec 11 may use 18 units of advanced anthropology courses, or 18 units of advanced economics, or 9 units of advanced anthropology and 9 units of advanced economics to fulfill the advanced social science requirement.

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 coursework. 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 class.

Scientific Writing Requirement

The scientific writing requirement can be satisfied by taking an appropriate course offered by any division, or by taking En 84. 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, BE, CS, EE, EAS, ME	E 10	E 11
Ay	Ay 30	Ay 31
Bi	Bi 24	same
BEM, Ec, PS	BEM/Ec/SS 20	same
ChE	ChE 126	Ch/ChE 91
Ch	Ch 90	Ch/ChE 91
En, H, HPS, Pl	En 84	same
GPS	Ge 109	Ge 13
Ma	Ma 10	Ma 11
Ph	Ph 70	same

First-Year Course Schedule, All Options

Differentiation into the various options begins in the second year.

		Units per term				
		1st		*2nd*		*3rd*
Ma 1 abc	Freshman Mathematics	9		9		9
Ph 1 abc	Freshman Physics	9		9		9
Ch 1 ab	General Chemistry	6		9		0
Bi 1	Biology and Biophysics of Viruses	0		0		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. A total load—including electives—of more than 48 units per term is considered a heavy load. Loads of more than 51 units for freshmen or 54 units for upperclass students require approval by the dean of students.

[1] *This course is offered in each of the three terms.*
[2] *The additional 6 units must be chosen from one of the following: APh/EE 9 (6 units), Bi 10 (6 units), Ch 3 b (6 units), Ch 4 ab (6 units per term), Ph 3 (6 units), or a more advanced laboratory course.*
[3] *Students entering 1996-97 or later years must take a menu course (currently Ay 1, Ch/APh 2, ESE 1, Ge 1, IST 1, or IST 4) 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.*
[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.*

Aerospace Minor

The aerospace minor is intended to supplement one of Caltech's undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major or who may wish to pursue a graduate program involving aerospace or aeronautical engineering. Students completing the aerospace minor requirements will have the phrase "minor in aerospace engineering" added to their transcripts.

Ae Minor Requirements

1. Complete Ae 105 abc.
2. Complete a second three-term 100-level Ae class, chosen from Ae 101 abc, 102 abc, 103 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 obtain a grade of B or higher. Courses that are used to satisfy the aerospace minor cannot be used to satisfy course requirements in the major options. Courses taken as part of the aerospace minor are counted toward the total 486-unit Institute graduation requirements. A typical course sequence would be to take Ae 105 abc and the second Ae course in the senior year.

Applied and Computational Mathematics Option

The undergraduate option in applied and computational mathematics is for 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. The program is similar in general outline to the mathematics option, with additional requirements to ensure a balance between courses that develop mathematical concepts and courses that show the interplay of these concepts with a variety of applications. Complete programs will be worked out with faculty advisers.

Option Requirements

1. Ma 5 abc or Ma 108 abc, and ACM 95 abc, ACM 106 abc, and E 10.
2. An approved sequence of three one-quarter courses to be selected from the following: ACM 101 abc, ACM 104, ACM 105, ACM 113, ACM 116, ACM/ESE 118, ACM 126 ab, 216, 217.
3. One of the following (or an approved three-term combination totalling at least 27 units): Ma/CS 6 abc, Ma 109 abc, Ma 110 abc, Ma 120 abc, Ma 121 abc, Ma 122 a, EE/Ma 126 ab, EE/Ma/CS 127, CS/EE/Ma 129 abc, Ma151abc.
4. One 27-unit 100 or higher level course in science or engineering not in ACM or Ma and approved by the student's adviser.
5. Passing grades must be obtained in a total of 486 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
ACM 95 abc	Intro. Methods of Applied Math.	12	12	12
ACM 11	Intro. to Matlab and Mathematica	6	-	-
	HSS Electives	9	9	9
	Electives	-	9	27
		45	48	48

Third Year

Ma 5 abc	Introduction to Abstract Algebra	9	9	9
or				
Ma 108	Classical Analysis			
ACM 106 abc	Intro. Methods of Comput. Math.	9	9	9
	HSS Electives	9	9	9
	Electives[1]	18	18	18
		45	45	45

Fourth Year

	HSS Electives	9	9	9
	Electives[1]	36	27	27
		45	36	36

[1] *See items 2, 3, and 4 under option requirements.*

Applied Physics Option

The applied physics option is designed to extend knowledge of the principles of pure physics to applications pertinent to applied physics or engineering. Research in applied physics typically centers on problems of technological concern. The applied physics option draws its faculty from the Divisions of Physics, Mathematics and Astronomy; Engineering and Applied Science; Chemistry and Chemical Engineering; and Geological and Planetary Sciences. The interdisciplinary nature of this option allows a flexibility and range in curriculum, appropriate to the student's particular research interests, that may result in a mixture of courses and research in different divisions.

Specific subject areas of interest in the program cover a broad spectrum of physics related to important fields of technology. Photonics areas include 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 is focused on nanostructured materials and devices, wide bandgap semiconductors and heterostructures for optoelectronics, photovoltaics, novel memory devices, and spin-dependent transport. Biophysics topics include single-molecule-scale studies of the mechanics of DNA, proteins, and their assemblies. Plasma-physics research is concentrated on spheromak plasmas for fusion application, plasma processes occurring in the sun, and the dynamics of pure electron plasmas. Transport in fluids spans processes at low and high Reynolds numbers, including micro/nanofluidic, optofluidic, or biofluidic devices, optical trapping in fluids, dissipation behavior in cantilever arrays, pattern formation and phase separation in thin-films or bulk layers, cellular, pulmonary, ocular, or cardiovascular flows, thin-film patterned growth by chemical vapor deposition and etching, convection-diffusive problems, aeronautical flows, combustion, etc.

The undergraduate curriculum attempts to reflect and maintain a close relationship with the various disciplines. This facilitates a transition to or from any of these, if at any time in the student's course of study and research this would be considered beneficial.

Any student whose grade-point average is less than 1.9 at the end of the academic year in the subjects listed below under option requirements may be refused permission to continue work in this option.

Option Requirements

1. E 10 and E 11. E 11 can be satisfied by three units of additional work associated with the senior thesis (APh 78 or 79), or by taking En 84 or Ph 70.
2. Any three of the following: APh/EE 9 b, APh 24, Ph 3, Ph 5, Ph 6, or Ph 7.
3. APh 17 abc, Ph 106 abc, and Ph 125 ab or Ch 125 ab.
4. ACM 95 abc.
5. Either APh 78 abc, or one term of APh 77 and one term of any of the following: APh 77, Ph 77, EE 91, Ch 6, Ae/APh 104 bc, and MS 90. Any substitutions or additions require prior approval of the option representative.
6. One additional three-term sequence of APh courses numbered over 100, which must include one of the following complete sequences: APh 101 abc, 105 abc, 114 abc, APh/Ph 115 ab plus additional one-term course, APh/EE 130, 131, and 132, APh 156 abc, 161, 162 plus additional one-term course, APh/EE 183, or APh 190 abc. 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.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 2 ab	Sophomore Physics	9	9	0
Ma 2 ab	Sophomore Mathematics	9	9	0
	HSS Electives	9	9	9
	Laboratory Electives[1]	6	6	6
APh 17 abc	Thermodynamics	9	9	9
	Other Electives	9	9	27
		51	51	51

Third Year				
Ph 125 ab	Quantum Mechanics	9	9	-
APh 110 abc	Topics in Applied Physics	2	2	2
ACM 95 abc	Intro. Methods of Applied Math.	12	12	12
	HSS Electives	9	9	9
	Other Electives[2]	18	18	27
		50	50	50
Fourth Year				
APh 78 abc	Senior Thesis, Experimental[3]	9	9	9
or				
APh 77	Laboratory in Applied Physics[3]	-	9	9
Ph 106 abc	Topics in Classical Physics	9	9	9
	Electives[2]	9	9	9
	HSS Electives	9	9	9
	Other Electives	18	9	9
		54	54	54

[1] *See item 2, option requirements.*
[2] *See item 6, option requirements.*
[3] *See item 5, option requirements.*

Suggested Electives
Students are encouraged to obtain a well-rounded course of study pursuant to the B.S. degree in applied physics. The option representative and/or undergraduate adviser will gladly assist students in choosing appropriate elective courses. Students ultimately interested in pursuing an advanced degree in applied physics or related fields are encouraged to complete a senior thesis project through APh 78 or 79.

Astrophysics Option

Modern astronomy—certainly as practiced at Caltech—is essentially astrophysics. With the goal of understanding the physical processes that govern the universe, its constituents, and their evolution, astronomy uses the apparatus and methodology of physics to gather and interpret data.

The astrophysics option is designed to give the student an understanding of the basic facts and concepts of astronomy today, to stimulate his or her interest in research, and to provide a basis for graduate work in astronomy/astrophysics. The sequence (Ay 20, 21) constitutes a solid introduction to modern astrophysics and may be taken either sophomore or junior year, with more advanced courses (Ay 101, 102, plus Ay electives) taken in the junior and senior years. It is desirable for a student to gain as broad a background as possible in related fields of science and engineering.

Attention is called to the fact that any student whose grade-point average is less than 1.9 at the end of an academic year in the subjects listed in the Division of Physics, Mathematics and Astronomy may, at the discretion of his or her department, be refused permission to continue the work in this option.

Option Requirements

1. Ay 20, 21, 101, 102, 30 or 141, 31, Ph 125 abc, and Ph 106 abc.
2. Ph 3 plus any two of 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. 54 additional units of Ay or Ph courses.
4. 27 additional units of science or engineering electives, of which 18 must be outside the Division of Physics, Mathematics and Astronomy. Core classes (see page 175) or other introductory-level courses 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.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 2 ab or Ph 12 abc	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
Ay 20	Basic Astronomy and the Galaxy	10	-	-
Ay 21	Galaxies and Cosmology	-	9	-
Ay 30	Intro. to Modern Research	-	3	-
	Physics Laboratory	6-9	6-9	6-9
	Core Menu Course	-	-	9
	HSS Electives	9	9	9
	Electives	0-6	0-3	15-21
		43-52	45-51	39-48
Third Year				
Ph 125 abc	Quantum Mechanics	9	9	9
Ph 106 abc	Topics in Classical Physics	9	9	9
Ay 101	The Physics of Stars	11	-	-
Ay 105	Astronomy Instrumentation Lab	-	9	-
	HSS Electives	9	9	9
	Electives	9-12	9-15	18-24
		47-50	45-51	45-51
Fourth Year				
Ay 31	Written Communication	-	-	3
Ay 102	Physics of the Interstellar Medium	-	9	-
	Astronomy or Physics Electives	18	18	18
	HSS Electives	9	9	9
	Electives	18-24	9-15	15-21
		45-51	45-51	45-51

An ability to present one's work is vital to a successful career in research and teaching. Ay 30 satisfies the oral communications requirement, but for further development, students are *also* urged to sign up for Ay 141 in their junior and senior years. 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. Nonthesis research credits may be earned through Ay 142 with a maximum of 9 units per term. Computational skills may be acquired through Ph 20–21 and/or ACM 106, or equivalent classes.

Suggested Electives

The student may elect any course offered in any division in a given term, provided that he or she has the necessary prerequisites for that course. The following courses are useful to work in various fields of astronomy and astrophysics: ACM 95, ACM 106, APh 23/24, Ay 105, Ay 121–127, EE 45, EE 91, EE/Ae 157, Ge/Ay 11 c, Ge 103, Ge/Ch 128, Ge 131, Ge/Ay 132, 133, 137, Ma 4, Ma 12, Ma 112, Ph 20–22, Ph 77, 101, 127, 129, 136, 199 (this is not necessarily a complete list).

Bioengineering Option

The undergraduate bioengineering option provides a foundation for graduate studies in 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. Students are required to complete core requirements in biomechanics, biomolecular engineering, cellular engineering, and physical biology of the cell.

Each student must specialize by selecting one of four tracks emphasizing the principles and experimental methods of a subdiscipline of bioengineering.

a. The devices track prepares students for graduate research in the design and fabrication of devices for manipulating, imaging, analyzing, or regulating biological systems.

b. The mechanics track prepares students for graduate research in elucidating the role of forces and flows in biological development, function and disease, and in exploiting this understanding to engineer biological and nonbiological mechanical systems based on these principles.

c. The synthetic biology track prepares students for graduate research in the fundamentals of biological circuit design at the molecular, cellular, and multicellular levels, emphasizing both the physical and information-processing aspects of biological circuits.

d. The self-guided track is intended to provide flexibility for students that wish to prepare for graduate research in an area of bioengineering that is not well served by a predefined track.

Each track culminates in a design lab that features the design and construction of a novel experimental system appropriate to the track. Students should notify the registrar of their track selection by the end of the third term of the first year. Students should present a plan for satisfying all degree requirements to their academic advisor by the end of the third term of the second year.

In addition to the Institute Core requirements, bioengineering students must satisfy requirements that provide additional grounding in physical chemistry, molecular biology, cell biology, experimental cell biology, mathematical methods, and computational methods.

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.

Option Requirements

1. BE 1, BE/Bi 105, BE/APh 161, ChE/BE 163, ChE/BE 169.
2. BE track: Satisfy the requirements for one of four 72-unit tracks. Track electives must be approved by the academic adviser as relevant to the selected track.
   a. Devices track: APh/EE 9 ab, EE 45, EE 111, EE 151, EE/BE 185, BE/EE 189, 9 units of track electives.
   b. Mechanics track: ME 19 a, ME 35 a, BE 152, Ae/APh 104 ab, BE 104, 18 units of track electives.
   c. Synthetic biology track: Ch 41 a; Bi/Ch 110; CDS 110 a or ChE 105; BE/CS/CNS/Bi 191 a; ChE 130; 21–24 units of track electives.
   d. Self-guided track: Students may choose to present a proposal for a self-guided track to the Bioengineering Undergraduate Committee (comprising the option representative and one BE faculty member representing each of the three established tracks). The proposed track should provide grounding in the principles and experimental techniques of a subfield of bioengineering and should culminate with a design lab.
3. Biology: Bi 8, Bi 9 (based on placement exams administered by the biology option, students with sufficient background may choose to take Bi/Ch 111 instead of Bi 8 and Bi/Ch 113 instead of Bi 9). One advanced biology course selected from Bi/Ch 111, Bi/Ch 113, Bi 114, Bi 117, Bi 122, Bi 145ab, Bi/CNS 150.
4. Chemistry: Ch 24 ab.
5. Mathematical and computational methods: ACM 95 ab; ACM 95 c (devices and mechanics tracks) or ACM/EE 116 (synthetic biology track); 9 units selected from CS 1–3, CS 11, Ph 20–22, ACM 11.
6. Experimental methods: Bi 10, one advanced biology lab class selected from BE/APh 162, Bi 180, Bi 227, ChE 130, track-specific lab requirements (see Requirement 2).
7. E 10, E 11.
8. Courses satisfying option requirements must be taken for grades (except when courses are only available on a pass/fail basis). Passing grades must be earned in a total of 486 units.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
First Year				
Ph 1 abc	Freshman Physics	9	9	9
Ma 2 abc	Freshman Mathematics	9	9	9
Ch 1 ab	General Chemistry	6	9	-
Ch 3 a	Fundamental Techniques of Experimental Chemistry	6	-	-
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Cell Biology Lab	-	-	6
BE 1	Frontiers in Bioengineering	-	1	-
	Menu Course	-	-	9
	HSS Electives	9	9	-
	PE	-	-	3
		39	46	45
Second Year				
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
Ch 24 ab	Intro. to Biophysical Chemistry	-	9	9
BE/Bi 105	Introduction to Biomechanics	-	-	9
	General and Track Electives	x	x	x
	HSS Electives	x	x	x
Devices track	APh/EE 9 ab	6	6	-
	EE 45	-	12	-
Mechan. track	ME 35 a	9	-	-
Syn. bio track	Ch 41 a	9	-	-
		42-45	42-45	42-45
Third Year				
ACM 95 ab	Intro. Methods of Applied Math	12	12	-
ChE/BE 163	Intro. to Biomolecular Engineering	-	-	9
BE/APh 161	Physical Biology of the Cell	-	9	-
E 10	Technical Seminar Presentations	x	x	x
	Computational Methods Req.	x	x	x
	HSS Electives	x	x	x
	General and Track Electives	x	x	x
Devices track	EE 111	9	-	-
	ACM 95 c	-	-	12
	BE/EE 189	-	-	12
Mechan. track	ACM 95 c	-	-	12
	BE 152	-	9	-
	ME 19 a	9	-	-
Syn. bio track	Bi/Ch 110	12	-	-
	ACM/EE 116	9	-	-
	ChE 130	-	-	9
		42-45	42-45	42-45

Fourth Year				
ChE/BE 169	Biomolecular Cell Engineering	9	-	-
E 11	Written Technical Communication	x	x	x
	HSS Electives	x	x	x
	Advanced Biology and Biology Lab Req.	x	x	x
	General and Track Electives	x	x	x
Devices track	EE 151	-	9	-
	EE/BE 185	-	-	9
Mechan. track	Ae/APh 104 ab	9	9	-
	BE 104	-	-	9
Syn. bio track	CDS 110 a or ChE 105	x	-	x
	BE/CS/CNS/Bi 191 a	-	9	-
		42-45	42-45	42-45

Suggested Track Electives

Devices track

BE 98, BE 99, EE 112, EE 113, EE 114 ab, ACM/EE 116, EE/BE 166.

Mechanics track

BE 98, BE 99, ME 19 b, ME 35 bc, ME 71, Ae/APh/CE/ME 101 abc, Ae/APh/CE/ME 102 abc, BE 141, BE 153, Ae/BE 242, BE/Ae 243, BE 251.

Synthetic biology track

BE 98, BE 99, CS 21, ChE/Ch 148, ChE/Ch 164, ChE/Ch 165, Bi 250 c, BE 251.

Biology Option

The undergraduate option in biology is designed to build on a solid foundation in mathematics and physical science by providing an introduction to the basic facts, concepts, problems, and methodologies of biological science. The option serves as a basis for graduate study in any field of biology or for admission to the study of medicine. Instruction is offered in the form of participation in the ongoing research programs of the division, as well as in formal course work. Course work emphasizes the more general and fundamental properties of living organisms, and areas of current research interest, rather than the traditional distinct fields within the life sciences.

The division encourages undergraduate participation in its research program and believes that research participation should be a part of each student's program of study. Students may elect to prepare an undergraduate thesis (Bi 90). Research opportunities may be arranged with individual faculty members, or guidance may be obtained from a student's individual faculty adviser in the division or from the biology undergraduate student adviser.

The requirements listed below for the biology option are minimal requirements. An adequate preparation for graduate work in biology will normally include additional elective research or course work in biology and/or advanced course work in other sciences or in mathematics. Flexibility to accommodate varied individual scientific interests, within the broad scope of biology, is achieved through the provision of elective courses, arrangements for individual research (Bi 22), and tutorial instruction (Bi 23). In addition, arrangements may be made to take courses at neighboring institutions in fields of biology that are not represented in our curriculum.

Premedical Program

The undergraduate course for premedical students is essentially the same as that for biology students and is intended as a basis for later careers in research as well as in the practice of medicine. It differs in some respects from premedical curricula of other schools; however, it has been quite generally accepted as satisfying admission requirements of medical schools.

It is recommended that all students contemplating application to medical school consult with the premed adviser, Angela Wood, at the Career Development Center, or David Chan, in the Division of Biology.

Option Requirements

1. Bi 8, Bi 9, Bi 117, Bi 122, Bi/CNS 150, and Ch 41 abc.
2. One advanced laboratory course chosen from Bi 123, Bi/CNS 162, Bi 180, Bi 227, or at least 12 units of independent research such as Bi 22.
3. Two courses chosen from Bi/Ch 110, 111, 113, and/or Bi/Ch 132.
4. Scientific writing requirement met by taking Bi 24 (six units), or by taking any other writing course such as En 84 or Ge 13 (three units) plus oral presentation at SURF Seminar Day or equivalent, with option representative approval.
5. None of the courses satisfying requirements 1–4 may be taken pass/fail, except Bi 22 and Bi 180.
6. At least six additional biology courses to a total of 146 units in biology must be taken and passed. Bi 1, Bi 2, and Bi 10 cannot be counted toward this total. Distribution requirement: these additional courses must be drawn from at least two of the following course "tracks" defined below: biochemistry, genetics, developmental biology, neurobiology, computational and systems biology, organismal and biomedical biology, cell biology, and interdisciplinary technology. At least four of these additional courses (including courses drawn from at least two tracks) must be taken for letter grades. At least two of these additional graded courses (from different tracks) must be for at least nine units.
7. Passing grades must be earned in a total of 486 units, including the courses listed above.

Biology Tracks

Individual classes may be relevant to more than one track, but classes cannot be double counted toward the distribution requirement. Courses included in the general option requirements that provide logical background for these tracks are indicated in parentheses; however, these cannot be counted toward the distribution requirement.

a. Biochemistry and molecular biology
   (Bi 8, Bi 9)
   Bi/Ch 110, 111, 113 (if not taken to satisfy item 3; no double counting)
   Ch 132, BMB/Bi/Ch 170 abc, Bi 189, Bi/Ch 206, Bi/Ch 211
   Note: Ch 24 and Ch 7 or Ch 145 are also recommended for students interested in this track.
b. Genetics
   (Bi 8, Bi 122)
   Bi 123, 180, 188, 190, 206
   Microbial biology subtrack: ESE/Bi 166, ESE/Bi 168 with Bi 180
c. Developmental biology and evolution
   (Bi 117, Bi 122)
   Bi 123, Bi/CNS 158, Bi 182, 188, 190, 204, 214
d. Neurobiology
   (Bi/CNS/Psy 150)
   Bi 133, 152, 156, 157, 162, 186, 202, 216, 217, 218, CNS/Bi 176
   Behavior/psychology subcluster: CNS/SS/Psy/Bi 102 ab, CNS/Bi/Psy 120, 131, 133, SS/Psy/Bi/CNS 140, Bi 152, Bi 156, 176, 216, 217, CNS/Bi 256
e. Computational and systems biology
   (Bi/CNS/Psy 150)
   CNS/Bi/SS/Psy 176, CNS/Bi/EE 186, CNS/Bi/Ph/CS 187, BE/CS/CNS/Bi 191 ab, Bi 204, CNS/Bi 221, CNS/Bi 247, CNS/Bi 256
   CS programming courses are highly recommended for those interested in this track.
f. Organismal
   Bi 114, 115, 145 ab, 157, 158, 188, 202, 214, 215
g. Cell biology
   (Bi 9)
   Bi 113, if not taken to satisfy requirement item 3
   Bi 145 ab, 189, 215
h. Interdisciplinary, technology approaches
   BE/Bi 105, Bi 177, 206, 227

Planning the Biology Course Schedule

Course requirements for biology are designed to be met by students taking Bi 8 and Bi 9 starting in their second year. However, many students interested in biology elect to take these courses in their first year. Those passing Bi 8 and Bi 9 in their first year may be excused from the Institute requirement to take Bi 1.

Students may place out of the option requirement to take Bi 8 or Bi 9 by passing an exam and then earning a passing grade in Bi/Ch 111 or Bi/Ch 113, respectively, instead. The exam for placing out of Bi 8 and Bi 9 is given in the summer before freshman year and is open to students who have scored a 5 on the advanced placement exam in biology.

Bi 10 is not required for the biology option but is commonly taken by biology students to meet the Institute introductory laboratory requirement.

Bi 123 is not required but is recommended for students planning to take any additional courses in genetics.

Prerequisites listed for individual biology courses are advisory, not compulsory. They indicate the kind of background that is assumed for the work level of the course. In general they may be waived with the instructor's permission.

Ch 24 ab is strongly recommended for students interested in postgraduate work in biology, as most graduate programs expect entering students to have taken a course in physical chemistry.

Additional courses of potential interest to biology majors include Ge 11 b, BE/APh 161, BE 163, and advanced geobiology courses.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
	HSS Electives	9	9	9
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ch 41 abc	Organic Chemistry	9	9	9
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Cell Biology Laboratory	-	-	6
	Electives	9-15	0-6	9-18
		45-51	45-51	42-51
Third Year				
	HSS Electives	9	9	9
Bi 117	Developmental Biology	-	9	-
Bi/Ch 110	Intro. to Biochemistry	12	-	-
Bi 122	Genetics	9	-	-
Bi 123	Genetics Laboratory	-	12	-
Ch 24 ab	Introduction to Biophysical Chemistry	-	9	9
	Electives	15-21	15-21	27-33
		45-51	54-60	45-51

Fourth Year

	HSS Electives	9	9	9
Bi 24	Technical Communication	6	-	-
Bi/CNS 150	Neurobiology	10	-	-
	Electives	23-26	36-42	36-42
		48-51	45-51	45-51

Business Economics and Management Option

The business economics and management (BEM) option provides students with the analytical tools to operate successfully in a modern volatile business environment. The emphasis is on strategy, design (markets, organizations, networks), finance, and law in a free-market competitive or strategic situation, as well as in a highly politicized environment. Today's business environment is complex; the required courses in this option are therefore highly analytical. The formal nature of the required courses can be complemented by case-study courses. For more information, go to http://www.hss.caltech.edu/ss.

Option Requirements

1. Ec 11, PS/Ec 172, BEM/Ec/SS 20 (or a similar writing/oral presentation course), BEM 101, Law 33.
2. BEM 103, BEM 105, BEM 106.
3. ACM/ESE 118 or Ec 122.
4. Five courses, to be chosen from the menu (may be taken pass/fail): BEM courses (excluding the ones listed under [1] and [2] above), Ec 105, 106, 116, 121 ab, 122, 123, 132, 135, 145, 155, Ec/PS 160 abc, PS 12, PS/Ec 173, Psy 15, 20, 115, ACM 113, ACM 116, Ma 112 a, Law 133, 134, 135. Other courses with permission of BEM option representative.
5. 45 additional units of science (including anthropology, economics, political science, psychology, social science), mathematics, and engineering courses; this requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by any course with a number less than 10 (may be taken pass/fail).
6. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
	Menu Course	-	-	9
Ec 11	Introduction to Economics	9	-	-
BEM 101	Introduction to Accounting	9	-	-
Law 33	Introduction to the Law	9	-	-
BEM 106	Competitive Strategy	-	-	9
PS/Ec 172	Noncooperative Games	-	-	9
	Electives[1]	-	27	18
		45	45	45
Third Year				
BEM 103	Introduction to Finance	9	-	-
BEM 105	Options	-	9	-
ACM/ESE 118	Methods in Applied Statistics and Data Analysis	9	-	-
	Electives[1]	27	36	45
		45	45	45
Fourth Year				
BEM/Ec/SS 20	Scientific Writing	-	6	-
	Electives[1]	45	39	45
		45	45	45

[1]See option requirements 4 and 5.

Chemical Engineering Option

The chemical engineering option is designed to prepare its students for either graduate study or research and development work in industry. This is accomplished by providing broad and rigorous training in the fundamentals of chemical engineering while maintaining a balance between classroom lectures and laboratory experience. The program also strives to develop in each student self-reliance, creativity, professional ethics, an appreciation of the societal impact of chemical engineering, and an understanding of the importance of continuing intellectual growth.

Chemical engineering involves applications of chemistry, physics, mathematics, and, increasingly, biology and biochemistry. In addition to these disciplines, the chemical engineering curriculum includes the study of applied and computational mathematics, fluid mechanics, heat and mass transfer, thermodynamics, chemical kinetics and chemical reactor design, and process control. Because of this broad-based foundation that emphasizes basic and engineering sciences, chemical engineering is perhaps the broadest of the engineering disciplines.

Because many industries utilize some chemical or physical transformation of matter, the chemical engineer is much in demand. He or she may work in the manufacture of inorganic products (ceramics, semiconductors, and other electronic materials); in the manufacture of organic products (polymer fibers, films, coatings, pharmaceuticals, hydrocarbon fuels, and petrochemicals); in other process industries; or in the biotechnology, pharmaceutical, or biomedical industries. Chemical engineering underlies most of the energy field, including the efficient production and utilization of coal, petroleum, natural gas, and newer technologies such as biofuels, fuel cells, and solar energy conversion technologies. Air and water pollution control and abatement and the study of climate change are also within the domain of expertise of chemical engineers. The chemical engineer may also enter the field of biochemical engineering, where applications range from the utilization of microorganisms and cultured cells, to enzyme engineering and other areas of emerging biotechnology, to the manufacture of foods, to the design of artificial human organs.

Key educational objectives of our chemical engineering curriculum focus 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. The senior laboratories integrate design with the construction and experimental evaluation of a system, process, or component.

Freshman and sophomore students normally take the core courses in mathematics, physics, chemistry, and biology (Ma 1 abc, Ma 2 ab, Ph 1 abc, Ph 2 ab, Ch 1 ab, and Bi 1). They take the sophomore chemistry labs (Ch 3a [or Ch 3 x] and Ch 3 b). They also take the second-year organic chemistry course (Ch 41 abc) and the basic chemical engineering courses (ChE 63 ab and ChE 64). It is strongly recommended that they also take a course in computer programming (e.g., CS 1, CS 2, or ACM 11).

Undergraduate research is emphasized, and students are encouraged, even in the freshman year, to participate in research with the faculty. In order to obtain a basic intellectual background, all students take courses in the fundamentals of chemical engineering through the junior year. During the junior and senior years, students diversify into one of four tracks (biomolecular, environmental, materials, or process systems) where they pursue concentrated study in their chosen area of chemical engineering. An optional senior thesis provides an opportunity to pursue independent research in lieu of one of the senior laboratories.

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 under the Division of Chemistry and Chemical Engineering may, at the discretion of the faculty in this division, be refused permission to continue the work in this option.

Option Requirements

1. Ch 3 b, Ch 41 abc, ChE 63 ab, ChE 64, ACM 95 abc, Ch 21 a, Ch 21 b (or Ch 24 a)[1], ChE 101, ChE 103 abc, ChE 105, ChE 126, Ch/ChE 91 (or En 84), three science/engineering electives (two if ChE 90 ab is selected), and one of Ec 11, BEM 101, or BEM 103[2].
2. Completion of a track (biomolecular, environmental, process systems, or materials), each consisting of eight 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: Bi/Ch 110, BE 151–153, [ChE/BE 163 or ChE/BE 169], [ChE 130 or ChE 90 ab], two additional bioengineering or related electives.
   b. Environmental track: ESE/GE 148 abc, [ChE 128 or ChE 90 ab], four additional ESE or related courses.
   c. Process systems track: ChE 110 ab, [ChE 128 or ChE 90 ab], five engineering electives.
   d. Materials track:
      i. ChE 128 or ChE 90 ab.
      ii. One course on materials synthesis and processing: Ch/ChE 147[3], ChE 115 or MS 133.
      iii. One pair of courses on the physical basis of structure and properties selected from [Ch 120 a and ChE/Ch 148[3]], or [MS 131 and (MS 130 or MS 132)], or MS 115 ab, or APh 114 ab.
   iv. Four materials science elective courses; these may be any combination of the remaining courses from those listed above, and/or any of the following courses: ChE/Ch 155, ChE/Ch 164, Ae/AM/CE/ME 102 abc, Ae/Ge/ME 160 ab, Ae/AM/MS/ME 213, Ae/AM/CE/ME 214 abc, AM/ME 165 ab, APh 109, Ch 121 ab, Ge 114 a, or any MS courses.
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.

[1] *May be taken in junior or senior year.*
[2] *These 9 units partially satisfy the Institute requirements in humanities and social sciences.*
[3] *Given in alternate years.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ch 3 b	Experimental Procedures of Synthetic Chemistry	-	-	8
Ch 41 abc	Organic Chemistry	9	9	9
ChE 63 ab	Chemical Engineering Thermodynamics	-	9	9
ChE 64	Principles of Chemical Engineering	9	-	-
	HSS Electives	9	9	18
		45	45	44
Third Year				
ACM 95 abc	Intro. Methods of Applied Math.	12	12	12
ChE 103 abc	Transport Phenomena	9	9	9
ChE 101	Chemical Reaction Engineering	-	9	-
ChE 105	Dynamics and Control of Chemical Systems	-	-	9
Ch/ChE 91	Scientific Writing	-	-	3
	ChE, Ch, track courses, and electives[1]	18	9	-
	HSS Electives	9	9	9
		48	48	42
Fourth Year				
ChE 126	Chemical Engineering Lab	9	-	-
	ChE, Ch, track courses, and electives[1]	36	36	18
	HSS Electives	-	9	18
		45	45	36

[1] *See option requirements.*

Chemistry Option

Study in the chemistry option leads, especially when followed by graduate work, to 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. To satisfy the Institute chemistry requirement, students may substitute at least two terms from Ch 21 ab or Ch 41 ab for Ch 1 ab only after passing the chemistry placement exam. Exceptions will be granted only by petition to the chemistry curriculum and undergraduate studies committee. Students who did not pass the placement exam may take Ch 1 and Ch 41 simultaneously, but Ch 1 ab must be passed to satisfy the Institute chemistry requirement. The one-term required laboratory course (Ch 3 a) presents basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. The laboratory in the following two terms (Ch 4 ab), normally taken concurrently with Ch 41, introduces the student to methods of synthesis, separation, and instrumental analysis used routinely in research. Qualified students, with the instructor's consent, are allowed to substitute either Ch 3 b or Ch 4 a 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 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.

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 pages) 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 (of maximum five pages) at the end of each of the first two terms of Ch 82, describing the current status of the research work and any results obtained. Upon evidence of satisfactory effort, the student will be allowed to continue his/her senior thesis.
4. A thesis of approximately 20 pages (excluding figures and references) will be presented to the mentor and the CUSC at the end of the third term of Ch 82. An oral thesis defense will be arranged by the CUSC. The thesis must be approved by both the research mentor and the CUSC.

5. Upon approval by the research mentor and the CUSC, the Ch 91 requirement for graduation may be satisfied by the written thesis and the progress reports from the first two quarters of Ch 82. If the thesis is being completed during the spring quarter of the senior year, a draft of the thesis is to be submitted by Add Day.

Double Majors
For students simultaneously pursuing a degree in a second option, courses taken as *required* courses for that option can also be counted as chemistry electives (requirement 3, below) where appropriate. However, courses that count toward the electives requirement in the other option cannot simultaneously be counted toward satisfying the elective requirement in chemistry.

The courses listed below would constitute a common core for many students in the option.

Any student of the chemistry option whose grade-point average is less than 1.9 will be admitted to the option for the following year only with the special permission of the Division of Chemistry and Chemical Engineering.

Option Requirements

1. Ch 14 (or ESE 142), Ch 21 abc (or Ch 21 a, Ch 24 ab), Ch 41 abc, Ch 90.
2. A minimum of five terms of laboratory work chosen from Ch 4 ab, Ch 5 ab, Ch 6 ab, Ch 7, Ch 10 c (if taken freshman or sophomore year), Ch 15, and Bi 10.
3. A minimum of five terms of advanced chemistry electives taken for a letter grade from chemistry course offerings at the 100 and 200 level, including cross-listed offerings such as Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi/Ch 132, and ChE/Ch 164, but excluding Ch 180 and Ch 280.
4. Passing grades must be earned in the courses that constitute the approved program of study, including those listed above. None of the courses satisfying option requirements may be taken pass/fail.
5. Passing grades must be earned in a total of 486 units, including courses listed above.[1]

[1] *No more than 27 units of Ch 80 will count toward the 486-unit requirement.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ch 41 abc	Organic Chemistry	9	9	9
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ch 4 ab	Synthesis and Analysis of Organic and Inorganic Compounds	9	9	-
Ch 14	Chemical Equilibrium and Analysis	-	-	6
	Electives	9-12	9-12	30-33
		45-48	45-48	45-48
Third Year				
Ch 5 a	Advanced Techniques of Synthesis	-	-	12
or	and Analysis			
Ch 5 b		-	9	-
Ch 15	Chemical Equilibrium and Analysis Laboratory	10	-	-
Ch 21 abc	Physical Chemistry	9	9	9
or				
Ch 21 a, Ch 24 ab				
Ch 90	Oral Presentation	-	3	-
Ch/ChE 91	Scientific Writing	-	-	3
	Electives	26-29	24-36	21-36
		45-48	45-48	45-48
Fourth Year				
Ch 6 a	Physical and Biophys. Chemistry Lab			
or		-	10	-
Ch 6 b		-	-	10
or				
Ch 7	Advanced Experim. Methods in Bioorganic Chemistry	-	-	9
	Electives	45-48	35-48	26-48
		45-48	45-48	45-48

This typical program is not specifically required for graduation in the option, nor is it in any sense a complete program. Students are expected to work out individual programs suitable for their interests and professional goals in consultation with their advisers. Several representative programs, including sets of possible electives, are shown below. These may well approximate choices by students who intend to do graduate work in conventional areas of chemistry.

Suggested Representative Courses of Study for Those Intending Graduate Work in Particular Areas of Chemistry

	Second Year	*Third Year*	*Fourth Year*
Inorganic Chemistry	Ch 4 ab, Ch 5 a, Ch 41abc, Ch 102, Ma 2 ab, Ph 2 ab, HSS elective, other elective	Ch 5 b[1], Ch 14, Ch 21 abc, Ch elective(s)[2], Ch laboratory[3], Ch 80, Ch 90, Ch/ChE 91 HSS elective	Ch 6 a or 6 b, Ch electives[2,3], Ch 80, HSS elective
Chemical Physics	Ch 4 ab, Ch 21 abc[4], Ch 6 ab[4], Ch 14, Ma 2 ab, Ph 2 ab, HSS elective	Ch laboratory[5], Ch 41 abc[4], Ch elective(s)[6], Ch 80, Ch 90, ACM 95 abc, Ch/ChE 91 HSS elective	Ch 125 abc, Ch electives[5,6], Ch 80, HSS elective
Organic Chemistry	Ch 4 ab[1], 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)[7], Ch laboratory[3], Ch 80, Ch 90, Ch/ChE 91 HSS elective	Ch 6 a or Ch 6 b, Ch electives[3,7], 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[8], Ch 7, Ch 14, Ch 21 a, Ch 24 ab (or Ch 21 bc), Ch 80 (or Bi 22), Ch 90, Ch/ChE 91 Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi 10, HSS elective	Ch 6 a or 6 b, Ch (Bi) electives[8,9], Ch 80 (or Bi 22), HSS elective

[1] *Requires Ch 4 ab.*
[2] *Ch 112, 117, 120 ab, 121 ab, 122 abc, 135 ab, Ch/ChE 140, Ch 143, 144 ab, Ch/ChE 147, Ch 154 ab, ChE/Ch 155, ESE/Ch/Ge 175 abc, Ch 212, 213 abc, 221.*
[3] *Ch 6 ab, 7, 15, Bi 10.*
[4] *Students without sufficient math preparation may delay Ch 21 abc and Ch 6 ab until their junior year and take Ch 5 ab and Ch 41 abc during their sophomore year.*
[5] *Ch 5 ab, Ch 15, Bi 10.*
[6] *Ch 120 ab, 121 ab, 126, Ge/Ch 128, 135 ab, Ch/ChE 140, Ch 144 ab, Ch/ChE 147, ChE/Ch 148, ChE/Ch 164, Ch 166, 221, 227 ab, Ph 106 abc.*
[7] *Ch 112, 120 ab, 121 ab, 122 abc, 135 ab, 143, 144 ab, 145, 146, Ch/ChE 147, Ch 154 ab, ChE/Ch 155, ESE/Ch/Ge 175 abc, Ch 242 ab, 247.*
[8] *Ch 5 ab, 15, 6 ab, 7.*
[9] *Ch 122, Bi/Ch 132, Ch 143, 144 ab, 145, 146, 154 ab, BMB/Bi/Ch 170, Ch/Bi 231, Ch 242 ab, 244, 247.*

Suggested Elective Courses for the Chemistry Option

1. *Chemical Engineering:* ChE 10, 63, 80, 101, 103, 151, 174.
2. *Biology:* Bi 9, 122, 114, 156, 180.

3. *Engineering:* ACM 95, APh/EE 9, CS 1, CS 2.
4. *Physics:* Ph 3–7, 106, 125, 129, 127.
5. *Humanities:* Ec 11, L 102 or L 130.
6. *Miscellaneous:* Ay 1, Ch/APh 2, Ch 10, ESE 1, MS 115, Ge 1, Ge 140, Ma 108.

Computer Science Option

Study in the computer science option emphasizes rigor and creativity, and is good preparation either for graduate study followed by a research career, or for a variety of professional or entrepreneurial occupations.

The option introduces students to the mathematical and engineering foundations of the discipline. It provides considerable flexibility in course selection, together with a capstone project giving an opportunity for independent work in an area of the student's choice. Individual programs will be worked out in consultation with faculty advisers (the materials at www.cs.caltech.edu/academics/undergrad_study.html may be helpful for this purpose).

Any student in the computer science option whose grade-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.

Option Requirements

1. CS 1; CS 2; CS 4; Ma/CS 6 a or Ma 121 a; CS 21 or CS/EE/Ma 129 a; CS 24; CS 38; E 10, E 11.
2. One of the following:
   a. Any of the following three-quarter sequences involving a large project in their last quarter: CS 141 abc; CS/EE 143, 144, 145; CS/EE 181abc; CS/EE/Ma 129 abc; CS 139 abc; CS/CNS/EE 154, 155, 159; CS/CNS 174 and two other CS 170-series courses.
   b. A laboratory project in computer science extending at least two quarters and totaling at least 18 units (normally in CS 81 or CS 90), approved for this requirement by the student's adviser and the CS undergraduate option representative.
   c. Thesis (CS 80 abc) supervised by a CS faculty member.
3. A total of 63 CS units that are not applied to requirement (1), and that are either numbered CS 114 and above or are in satisfaction of requirement (2).
4. In addition to the above requirements, 36 units in Ma, ACM, or CS; 18 units in EAS or Ma; and 9 units not labeled PE or PA.
5. Units used to fulfill the Institute Core requirements do not count toward any of the option requirements. Pass/fail grading cannot be elected for courses taken to satisfy option requirements. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	2nd	3rd
Second Year				
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
CS 1	Intro. to Computer Programming[1]	9	-	-
CS 2	Intro. to Programming Methods[1]	-	9	-
CS 4	Fundamentals of Computer Program.	-	9	-
Ma/CS 6 a	Intro. to Discrete Math	9	-	-
CS 21	Decidability and Tractability	-	9	-
CS 24	Intro. to Computing Systems	-	-	9
CS 38	Introduction to Algorithms	-	-	9
	HSS Electives	9	-	9
	Other Electives	-	-	9
		45	45	36
Third Year				
	CS Courses	9	9	9
	CS Project	9	9	9
	HSS Electives	9	9	9
E 10	Technical Seminar Presentations	-	-	3
	EAS/Ma Courses	9	9	9
	Other Electives	9	9	-
		45	45	39
Fourth Year				
	CS Courses	9	-	-
	HSS Electives	9	18	9
	EAS/Ma Courses	9	9	9
	Other Electives	18	9	18
		45	36	36

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

Control and Dynamical Systems Minor

Control and dynamical systems (CDS) may be pursued as a minor concentration by undergraduates who are taking degrees in science, mathematics, or engineering. The CDS minor is intended to supplement one of Caltech's normal undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major or who may wish to pursue a graduate program involving control or dynamical systems. Students completing the minor requirements below in CDS will have the phrase "minor in control and dynamical systems" added to their transcripts and their graduating degree materials.

CDS Minor Requirements

1. Complete CDS 110 a and CDS 140 a.
2. Compete nine additional units in CDS courses, chosen from CDS 110 b, 140 b, 212, or 270.
3. Complete a three-term senior thesis approved by the CDS faculty.

All CDS courses to be applied to fulfill the CDS minor requirements must be taken for grades and students must obtain a grade of B or higher. The senior thesis requirement may be satisfied by completing a three-term senior thesis in the student's major option but on CDS subject matter, with the approval of the thesis topic by the CDS option representative, or by taking CDS 90 abc.

Courses that are used to satisfy the CDS minor cannot be used to satisfy course requirements in the major options, with the exception that CDS 110 a 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 Institute graduation requirements.

A typical course sequence would be to take either CDS 110 a or CDS 140 a in the junior year, followed by the remaining courses and the senior thesis in the senior year. Alternatively, it is possible to take all requirements in the senior year. In addition to the requirements above, CS 1 and CS 2 are highly recommended.

Economics Option

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

The option is sufficiently flexible that students can combine their pursuit of economics with studies in engineering, mathematics, or science. The core of the option consists of an economic theory component, a data analysis component, an applied microeconomic component, and a macroeconomic/growth component. Students are strongly encouraged to supplement this core with additional electives in economics, political science, and mathematics.

Option Requirements

1. Ec 11 and BEM/Ec/SS 20.
2. Theory: Ec 121 ab and PS/Ec 172.
3. Data analysis: one of Ma 112 a or ACM/ESE 118, followed by Ec 122.
4. Applied microeconomics: one of Ec 105, 118, or 145.
5. Macroeconomics and growth: one of Ec 123, Ec/SS 129, 130, or Ec 140.
6. 45 additional units of advanced economics and social science courses. (Courses that are used to fulfill the Institute advanced social science requirement [courses numbered 100 and above]

will also count toward this requirement.) Students may also take classes from the following list in partial fulfillment of this requirement: any BEM course except BEM 101; ACM 113, ACM 116. Students who take both Ma 112 a and ACM 118 may count one of them under requirement 3 and the other one for this requirement.

7. 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.
8. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
	Menu Course	-	-	9
Ec 11	Introduction to Economics	9	-	-
PS 12	Introduction to Political Science	-	-	9
	Electives[1]	18	27	27
		45	45	45
Third Year				
Ec 105	Industrial Organization	-	9	-
Ec 121 ab	Theory of Value	9	9	-
PS/Ec 172	Game Theory	-	-	9
Ec 122	Econometrics	9	-	-
Ec 123	Macroeconomics	-	-	9
Ma 112 a	Statistics	9	-	-
	Electives[1]	18	27	27
		45	45	45
Fourth Year				
BEM/Ec/SS 20	Scientific Writing	-	6	-
	Electives[1]	45	39	45
		45	45	45

[1] *See option requirements 5 and 6.*

Electrical Engineering Option

The main objective of the electrical engineering program is to prepare its students for either graduate study or research and development work in government or industrial laboratories. This objective is consistent with the Institute's mission since 1921 (as quoted on page 9). It accomplishes this by building on the core curriculum to provide a broad and rigorous exposure to the fundamentals (e.g., math, science, and 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 emphasizes the problem-formulation, system-design, and solving skills that are essential to any engineering discipline. The program also strives to develop in each student self-reliance, creativity, teamwork ability, professional ethics, communication skills, and an appreciation of the importance of contemporary issues and lifelong intellectual growth.

Students electing this option will normally choose to take APh/EE 9 as a freshman-year elective and the introductory seminar EE 1. The formal study of electrical engineering begins in the sophomore year with digital electronics, EE/CS 51, 52, semiconductor sensors and actuators, EE 40, and then the theory and laboratory practice of analog circuits, EE 45. The junior year features the fundamentals of signals and systems and digital signal processing, EE 111; a course on feedback control systems, EE 113 or CDS 110 a; an introduction to analog and digital communications, EE 160; electromagnetic engineering, EE 151; and an analog electronics laboratory, EE 90. In the senior year, the student will be asked to demonstrate his or her ability to formulate and carry out a design project through independent research or either a senior thesis, EE 80 abc, or two courses selected from the senior project design laboratory, EE 91 ab, EE/CS 53, and CS/EE/ME 75 c. In addition, the student, especially in the senior year, will have a significant opportunity to take elective courses that will allow him/her to explore earlier topics in depth, or to investigate topics that have not been covered previously. (See the "suggested electives" section, page 207.)

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.

Option Requirements

1. APh/EE 9 ab, EE 1.
2. ACM 95 ab, ACM/EE 116.
3. EE 40, 45, 111, 151, 160, and either EE 113 or CDS 110 a.
4. EE/CS 51, EE/CS 52, EE 90.
5. EE 80 abc, or one term of EE 91 and one course selected from an additional term of EE 91, EE/CS 53, and CS/EE/ME 75 c (note that CS/EE/ME 75 ab does not satisfy this requirement).
6. E 10 and E 11.
7. In addition to the above courses, 27 units selected from any EE course numbered over 100, or any cross-listed courses numbered over 100 that include EE in the listing.
8. Passing grades must be earned in a total of 486 units, including courses listed above.

Typical Course Schedule[1]

		Units per term		
		1st	2nd	3rd
Second Year				
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives[2]	9	9	9
EE 40	Semiconductor Sensors and Actuator	-	-	9
EE 45	Electronics Laboratory	-	-	12
EE/CS 51	Principles of Microprocessor Systems	12	-	-
EE/CS 52	Microprocessor Systems Laboratory	-	12	-
	Electives	-	-	9
		39	39	39
Third Year				
E 10	Technical Seminar Presentations	3	-	-
E 11	Written Technical Communication	-	3	-
ACM 95 ab	Intro. Methods of Applied Math.	12	12	-
	HSS Electives[2]	9	9	9
ACM/EE 116	Intro. to Stochastic Processes	9	-	-
EE 113	Feedback and Control Circuits	-	-	12
EE 151	Electromagnetic Eng.	-	9	-
EE 111	Signals, Systems, and Transforms	9	-	-
EE 90	Analog Electronics Project Lab	-	-	9
EE 160	Communication-System Fundamentals	-	9	-
	Electives	-	-	9
		42	42	39
Fourth Year (for project)				
	HSS Electives[2]	9	9	9
EE 91 ab[3]	Experimental Projects in Electronic Circuits	12	12	-
	EE Electives	9	9	9
	Electives	9	9	18
		39	39	36
Fourth Year (for thesis)				
	HSS Electives[2]	9	9	9
EE 80	Senior Thesis	9	9	9
	EE Electives	9	9	9
	Electives	9	9	18
		39	39	36

[1] *A student who follows this "typical schedule" exactly, and who takes APh/EE 9 ab as a freshman, will have taken more than 500 units prior to graduation, whereas only 486 are required. This means that by taking fewer electives than given in the typical schedule, the student can take lighter loads and have considerable flexibility in arranging his or her individual schedule.*

[2] *See Institute requirements for specific rules regarding humanities and social sciences.*

[3] *See option requirement 5.*

Suggested Electives
First-year students interested in electrical engineering should take APh/EE 9 ab, which is an EE option requirement (though it need not be taken freshman year).

Suggested elective courses for the second, third, and fourth year for various specializations within electrical engineering are given below. Students interested in other areas of specialization or interdisciplinary areas are encouraged to develop their own elective program in consultation with their faculty adviser.

Bioengineering
Second Year: BE/Bi 105, Bi 9, Bi 10, APh 17 abc
Third and Fourth Year: Bi/Ch 110, Bi/Ch 113, BE 141, EE/BE 166, EE/BE 185, CNS/Bi/EE 186, CNS/CS/EE 188.

Communications and Signal Processing
Second Year: Selected from APh 17 abc, APh 23, APh 24, EE/CS 53
Third and Fourth Year: EE 112, EE/Ma 126 ab, 127 ab, EE 128 ab, 161, 163 ab, 164, 167, EE/APh 131, APh/EE 130, 132, Ma 112 a.

Control
Second Year: APh 17 abc
Third and Fourth Year: CDS 110 ab, 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 114 ab, 124, 125, 153, CS/EE 181 abc, and selections from EE 112, CS 185 abc, EE/APh 180, EE 119, EE 160, EE 128 ab.

Microwave and Radio Engineering
Second Year: APh 23, APh 24, APh 17 abc
Third and Fourth Year: EE 153, EE/Ae 157 ab, EE 114 ab, EE/APh 131, APh/EE 130, 132, APh/EE 183.

Optoelectronics
Second Year: APh 23, APh 24, APh 17 abc
Third and Fourth Year: APh/EE 130, 132, APh 105 abc, APh 114 abc, APh/EE 183, APh 190 abc, EE/APh 131, EE 153.

Solid-State Electronics and Devices
Second Year: APh 17 abc
Third and Fourth Year: APh/EE 183, and selections from APh 105 abc, APh 114 ab, EE 153, EE/BE 185, EE 187.

Engineering and Applied Science Option

The engineering and applied science (EAS) option offers students the opportunity for study in a wide variety of challenging areas of science and technology and includes concentrations in computation and neural systems, environmental science and engineering, and materials science. In addition, the EAS option offers students the possibility of designing a customized course of study that has breadth, depth, and rigor similar to the concentrations listed above.

The aim of the EAS option is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program builds on the core curriculum to combine individual depth of experience and competence in a particular chosen engineering specialty, and a strong background in the basic and engineering sciences, with laboratory and design culminating in a capstone design experience. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

The first year of the four-year course of study leading to a Bachelor of Science degree is common for all students of the Institute, although freshman elective subjects are available as an introduction to various aspects of engineering and applied science. At the end of the first year, students who elect the EAS option are assigned advisers as close to their expressed field of interest as possible, and together with their advisers develop programs of study for the next three years. Beyond the Institute-wide requirements of physics, mathematics, and humanities, the EAS option requires one year of applied and computational mathematics and a prescribed number of units selected from a wide variety of engineering and applied science courses. Engineering design (synthesis), as distinct from analysis, is considered an essential part of every engineer's capability. Advisers will expect students to select a sufficient number of courses that place emphasis on design.

Any student in the EAS option whose grade-point average is less than 1.9 at the end of the academic year in the subjects listed in the option requirements may be refused permission to continue to work in the EAS option.

Option Requirements

Students who have elected the EAS option must either choose one of the approved areas of concentration (see item 6 a below), or by the end of the third term of the sophomore year submit a written proposed customized course of study and obtain approval for it from the EAS option oversight committee (see item 6 b below).

The course of study must include each of the following elements:

1. 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.
2. a. 27 units of advanced EAS courses with the prefixes Ae, ACM, AM, APh, BE, CE, CNS, CS, CDS, EE, ESE, MS, or ME;

and

b. 27 additional units of either advanced EAS courses or advanced science courses offered by the Biology, CCE, GPS, or PMA divisions.

3. a. 9 units of laboratory courses taken from the following list: APh 77 bc, Ae/APh 104 bc, CE 95, CE 180, CS/CNS 171, 173, and 174, EE 45, EE/CS 52, 53, 54, EE 90, EE 91 ab, ESE 159, MS 90, MS 125, ME 72 ab, ME 90 bc, ME 96;

and

b. 9 units of additional laboratory courses either from the list in 3 a or from EAS courses with the word “laboratory” in the title, but excluding those courses for which freshman laboratory credit is allowed.

4. ACM 95 abc or Ma 108 abc or Ma 109 abc. None of these course sequences may be taken pass/fail.
5. E 10 or equivalent; E 11 or equivalent.
6. Courses used to satisfy requirements 1–5 above must also satisfy a depth requirement, which must be met by either:

a. the concentration requirements listed below for one of the following disciplines: computation and neural systems, environmental science and engineering, and materials science

or

b. a customized schedule of requirements that is similarly rigorous to 6 a, has both breadth and depth, and that includes a senior thesis or capstone design project, such as, but not restricted to EE 80 abc, CS 80 abc, ME 90 abc, or two terms chosen from EE 91 ab and EE/CS 53. To select this alternative, the student must submit a written proposal to, and obtain the approval of, the EAS option oversight committee. This approval must be obtained by the end of the third term of the sophomore year.

(Note: Students who meet the depth requirement by satisfying one of the five concentration requirements listed in 6 a will have both the EAS option and the name of the concentration listed on their transcript while students who satisfy the depth requirement using 6 b will have only the EAS option listed on their transcript.)

7. At least 117 units of EAS courses not including those used to satisfy requirements 3, 4, and 5 above. Concentrations marked with a dagger (†) in the list below include sufficient EAS courses to automatically satisfy this requirement; concentrations marked with an asterisk (*), and also the customized schedule given in 6 b, do not do so, in which case students will have to select sufficient additional EAS courses to bring the total to 117 units. Courses in ChE count toward this requirement.
8. All concentrations and the customized schedule of requirements described in 6 b shall include a major design experience.
9. Passing grades must be earned in at least 486 units, including those listed in requirements 1–8 above.

Discipline Concentration Requirements (to satisfy requirements 6 a and 8 above)

*Computation and Neural Systems**
CNS 100, Bi/CNS 150, CNS/Bi/Ph/CS 187, CNS/Bi/EE 186, CNS/CS/EE 188 (or IST 4), EE 111, CDS 101, Bi 8 (or Bi 9). CS 2 is required in addition to CS 1 for the CNS concentration. In addition, the laboratory course Bi/CNS 162 is required. The project for CNS/Bi/EE 186 shall be organized as a design project drawing on the ensemble of CNS disciplines.

Environmental Science and Engineering†
Thermodynamics (ChE 63 ab or ME 18 ab), transport processes (ChE 103 abc or ME 19 ab), environmental laboratory (ESE 159); a total of 4 courses covering all three of the areas of environmental chemistry (ESE 142, ESE/Ge/Ch 171, 172, or ESE/Ch/Ge 175), environmental physics (ESE/Ge 148 a, ESE/Ge 148 b, or ChE/ESE 158), and environmental biology (ESE/Ge 148 c, ESE/Bi 166, or ESE/Bi 168); ESE 90 (senior thesis) 18 units. ESE 159 satisfies requirement 8. Substitution of courses may be approved at the discretion of the concentration representative, provided they meet the overall EAS requirements.

Materials Science†
APh 17 ab or ChE 63 ab or ME 18 ab, MS 115 ab, MS 90, and three terms of MS 78 (senior thesis, which includes a major design experience). In addition, the student shall complete 45 units from the following list of restricted electives: ME 35 abc, APh 105 abc, APh 114 abc, APh/EE 130, APh/EE 183, Ch 120 ab, Ch 121 ab, Ch 125 abc, Ch/ChE 147, ChE/Ch 148, CS 11, Ge 114 ab, MS 105, MS 125, MS 130–133, MS 142, Ph 125 abc. Substitution of courses may be approved at the discretion of the concentration representative, provided they meet the overall EAS requirements.

Typical Course Schedules

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
	HSS Electives	9	9	9
	Electives	18	18	36
		45	45	45
Third Year				
ACM 95 abc or Ma 108 abc or Ma 109 abc		12	12	12
	HSS Electives	9	9	9
	Electives	24	24	24
		45	45	45

Fourth Year

E 10	Technical Seminar Presentations	-	3	-
	HSS Electives	9	9	9
	Electives	33	33	33
		42	45	42

Typical Course Schedules by Concentration

Variation of the course schedule from these examples should be made in consultation with the student's academic adviser and must satisfy the discipline concentration requirements listed above.

Computation and Neural Systems

	First Term	*Second Term*	*Third Term*
First Year	CS 1	CS 2	Elective
Second Year	CNS 100 EE 111	Bi 8	Elective
Third Year	Bi/CNS 150 CDS 101 ACM 95 a	CNS 186[1] ACM 95 b	Bi/CNS 162[1] ACM 95 c
Fourth Year	CNS 187 E 10	CNS 188	Elective

[1] *Offered biannually.*

Environmental Science and Engineering

	First Term	*Second Term*	*Third Term*
First Year	CS 1	Ch 3	ESE 1
Second Year	ChE 63 a or ME 18 a Engineering Elective	ChE 63 b or ME 18 b Engineering Elective	Engineering Elective
Third Year	ACM 95 a ChE 103 a or ME 19 a ESE Core	ACM 95 b ChE 103 b or ME 19 b ESE Core	ACM 95 c ChE 103 c ESE Core ESE Lab
Fourth Year	ESE Core	ESE 90 E 10	ESE 90 ESE Lab

Materials Science

	First Term	*Second Term*	*Third Term*
Second Year	APh 17 a MS 115 a	APh 17 b MS 115 b	Restricted Elective or MS 90

Third Year	ACM 95 a Restricted Elective	ACM 95 b Restricted Elective	ACM 95 c Restricted Elective or MS 90
Fourth Year	MS 78 a MS 131	MS 78 b MS 132 E 10	MS 78 c MS 133

English Option and Minor

The option in English provides students with a broad education in English and American literatures, their historical contexts, and different approaches to their study. During the senior year, English majors will enroll in En 99 ab with a faculty member chosen by mutual agreement. En 99 a is devoted to research and En 99 b to writing a substantial research paper. This paper provides the most important means for evaluating a major's progress in the rigorous study of English. The English option provides excellent preparation for students seeking careers in law, business, administration, and medicine. The emphasis on writing critical essays helps scientists and engineers develop the communication skills necessary for success in their fields.

All students are assigned an adviser who will help them select the courses best suited to their needs, including courses in fields such as history that may be relevant for work in the English option. Students will be expected to consult their adviser before registering for each quarter's work. It is recommended that English majors take at least one English or related course per term. Those who are preparing for graduate work in English should take more than the minimum requirements listed below, and should be prepared to take courses in several periods of English and American literature. All courses to be counted toward the option in English must be taken for grades except for Hum/En 5 or Hum/En 6 when taken in the first two quarters of the freshman year.

Option Requirements

1. En 99 ab.
2. 81 additional units of English courses numbered 99 and above. 27 of these units must include one course in British literature, one course in American literature, and one course in literature before 1850 (En 114, 116, 122, 125, 129). Courses cannot be counted twice in meeting these distribution requirements. Up to nine units of Hum/En 5 or Hum/En 6 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.

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

1. 72 units of English courses numbered 99 or above.
2. Nine units of Hum/En 5 or Hum/En 6 may be substituted for any nine of the 72 units required for the minor.
3. Nine units of En 98 may be substituted for any nine of the 72 units required for the minor.

Geology, Geobiology, Geochemistry, Geophysics, and Planetary Science Options

The aim of this undergraduate program is to provide thorough training in the geological and planetary sciences and, wherever possible, to integrate these studies with courses in mathematics, physics, chemistry, and biology taken during the student's earlier years at the Institute. Active involvement in research, particularly during the summer, is encouraged. For geologists, field work is important because it provides firsthand experience with geological phenomena that can never be satisfactorily grasped or understood solely from classroom or laboratory treatment. Options are offered in geology, geobiology, geochemistry, geophysics, and planetary science. Electives permit students to follow lines of special interest in related scientific and engineering fields. Those who do well in the basic sciences and at the same time have a compelling curiosity about the earth and the other planets are likely to find their niche in these options, especially if they enjoy grappling with complex problems involving many variables. Most students majoring in the earth and planetary sciences now pursue further training at the graduate level.

Under the geobiology option a student can be associated with either Biology or GPS. 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 spring term of their sophomore year in order to prepare for Ge 120 b the following summer.

Passing grades must be earned in a total of 486 units, including courses listed below. Any student whose grade-point average in science and mathematics courses is less than 1.9 at the end of an academic year may be refused permission to register in the geological and planetary science options.

Double Majors

For students simultaneously pursuing a degree in a second option, courses taken as required courses for that option can also be counted as Ge electives where appropriate. However, courses that count toward the electives requirement in the other option cannot simultaneously be counted toward satisfying the elective requirement in GPS.

Option Requirements

Geology Option Requirements

1. Ge 11 ab, Ge/Ay 11 c or Ge 11 d, Ge 13, 109.
2. ACM 95 abc or (Ch 41 abc and Ge 108) or (Ch 21 abc and Ge 108).
3. Ge 106, 112, 114 ab, 115 abc, 120 ab.
4. Ge 116 and 111 ab; or Ge 125 and Ge 11 d[1].
5. 15 units of elective courses in Ge or cross-listed with Ge.

[1] *If Ge 11 d is used to satisfy requirement 4, students must take Ge 11 c to satisfy requirement 1.*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planet. Sci.	9	9	9
Ge 13	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Ge 106	Intro. to Structural Geology	-	-	9
Ge 120 a	Field Geology Intro.[1]	-	-	6
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives	9	9	9
		36	36	39

Summer				
Ge 120 b	Field Geology Camp[1]	-	-	18
Third Year				
ACM 95 abc	Intro. Methods of Applied Math	12	12	12
Ge 112	Sedimentology and Stratigraphy	12	-	-
Ge 114 ab	Mineralogy	12	-	-
Ge 115 abc	Petrology and Petrography	-	6	12
Option 1:				
Ge 111 ab	Applied Geophysics	-	6	9
and Ge 116	Analytical Techniques	-	6	-
	HSS Electives	9	9	9
		45	39-27	42-33
Fourth Year				
Option 2:				
Ge 125	Geomorphology	12	-	-
and Ge 11d	Geophysics	-	9	-
	Geology Electives	9	-	6
	HSS Electives	9	9	9
		18-30	9-18	15

[1] Ge 120 ab is taught in alternate years. Some cohorts of students will take this course in their third year and the summer following.

Geobiology Option Requirements

1. Ge 11 ab, Ge/Ay 11c, Ge 13, 109.
2. Ch 41 abc and Bi/Ch 110.
3. Bi 8–10, 117, 122, ESE/Bi 166, Ge 114 a, Ge/ESE 170, Ge 112.
4. 9 units of geobiology electives from the following list: Bi 123, 180, Ch 4 ab, 5 ab, 15, Ge 121 ab.
5. 27 units of geobiology electives in geology, biology, chemistry, and/or environmental engineering to be chosen in consultation with adviser from the list in 4 or from the following list: Ge 11 d, 40, 41 abc, 100 abc, 106, 114 b, 115 abc, 116, 120 ab, 121 ab, 124 ab, 140, 142, Ge/ESE 149, Ge/Bi 244, 246, Ge 282 abc, BMB/Bi/Ch 170, Bi 22, 24, 90 abc, Bi/Ch 111, 113, Bi 115, 123, Bi/CNS 150, Bi 152, Bi/CNS 158, Bi 180, 182, 188, 190, 204, Bi/CNS 216, ESE 142, ESE/Ge 148 abc, 152, ESE/Ge/Ch 171, 172, 175 ab, Ch 4 ab, 5 ab, 7, 14, 15, 21 abc, 24 ab, 112, 145, 146, 154 ab, 212; Occidental College Ge 365.

		1st	2nd	3rd
		Units per term		
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
Ge 13	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Bi 8	Introduction to Molecular Biology	-	9	-
Bi 9	Cell Biology	-	-	9
Bi 10	Cell Biology Laboratory	-	-	6
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives	9	9	9
		36	45	39
Third Year				
ESE/Bi 166	Microbial Physiology	9	-	-
Ge 114 a	Mineralogy	9	-	-
Ch 41 abc	Organic Chemistry	9	9	9
Ge/ESE 170	Microbial Ecology	-	-	9
	HSS Electives	9	9	9
	Geobiology Electives	9	9	9
		45	27	36
Fourth Year				
Bi/Ch 110	Intro. to Biochemistry	12	-	-
Bi 117	Developmental Biology	-	9	-
Bi 122	Genetics	9	-	-
Ge 112	Sedimentology and Stratigraphy	12	-	-
	HSS Electives	9	9	9
	Geobiology Electives	-	9	18
		42	27	27

Geochemistry Option Requirements

1. Ge 11 ab and either Ge/Ay 11 c or Ge 11 d, Ge 13, Ge 109.
2. ACM 95 abc or (Ch 41 abc and ACM/ESE 118) or (Ch 21 abc and ACM/ESE 118).
3. Geochemistry students must take a total of 105 units from the core geochemistry list and the geochemistry elective list, including at least three courses from the core geochemistry list[1]. Core geochemistry: Ge 114 ab[2], 140, Ch 41 a, 21 a, ESE/Ge/Ch 171, Ge/ESE 149, Ge 116. Geochemistry electives: Ch 41 bc, 21 bc, 3 b, 4 ab, 6 ab, 14, 15, 102, ESE 142, Ge/ESE 143, ESE/Ge 148c, Ge/ESE 154, ESE 159, ESE/Ge/Ch 172, 175 ab, Ge 106, 115 abc, 120 ab, 127, 128, 132, 191, 212, 214, 215, 232, 236, Ge/Ay 133, APh 17 abc, MS 105, 115 ab, 125, 130–133.

[1] *Any units from either Ch 41 or Ch 21 that are used to satisfy requirement 2 may not be used to satisfy requirement 3.*
[2] *Students must take both Ge 114 a and Ge 114 b to count as one core geochemistry course.*

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
Ge 13	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
	Geochemistry Core or Electives	9	9	9
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives	9	9	9
		45	45	33
Third Year				
ACM 95 abc	Intro. Methods of Applied Math	12	12	12
	HSS Electives	9	9	9
	Geochemistry Core or Electives	18	18	18
		39	39	39
Fourth Year				
	HSS Electives	9	9	9
	Geochemistry Electives	9	9	9
		18	18	18

Geophysics Option Requirements

1. Ge 11 ab, Ge/Ay 11 c, Ge 13, 109.
2. ACM 95 abc.
3. Ge 111 ab, Ge 11 d.
4. 27 units of physics or mechanics electives: any non-GPS course numbers 100 or greater, relevant to the option and approved by the option representative, including ME 65, 66, AM 125 abc, Ae/Ge/ME 160, Ph 106 abc.
5. 36 units of geophysics electives (selected in consultation with adviser): Ge 161–168, Ge 211, 200-level courses.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
Ge 13	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives	9	9	9
		36	36	24
Third Year				
	Physics or Mechanics Electives	9	9	9
	HSS Electives	9	9	9
Ge 111 ab	Applied Geophysics Seminar	-	6	9
Ge 11 d	Geophysics	-	9	-
		18	33	27

Fourth Year				
	Geophysics Electives	18	18	9
	HSS Electives	9	9	9
		27	27	18

Planetary Science Option Requirements

1. Ge 11 ab, Ge/Ay 11 c, Ge 13, 109.
2. ACM 95 abc.
3. 27 units of advanced science courses selected from Ae/APh/CE/ME 101 abc, Ae/Ge/ME 160 ab, Ch 21 abc, Ph 101, 106 abc, 125 abc, which must include two consecutive terms of one of the multiterm courses.
4. 63 units selected from Ge 102, Ge/Ch 128, Ge 131, Ge/Ay 132, Ge/Ay 133, ESE/Ge 148 abc, Ge 150, 151, ESE/Ge 152, 153, 173, Ge 225 abc.
5. 27 units of additional science and engineering courses (selected in consultation with adviser and planetary science option representative), appropriate Ge courses, any of the courses listed above, or any of the following: ACM 101 abc, ACM/ESE 118, ME 35 abc, APh 17 abc, Ay 20, 21, 101, 102, ChE 63 ab, Ch 6 ab, CS 1–3, Ma 112 ab, ME 18 ab, 19 ab, 65, 66, AM 125 abc.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 abc	Intro. to Earth and Planetary Sci.	9	9	9
Ge 13	Scientific Writing	-	-	3
Ge 109	Oral Presentation	-	-	3
Ph 2 ab	Sophomore Physics	9	9	-
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS Electives	9	9	9
		36	36	24
Third Year				
ACM 95 abc	Intro. Methods of Applied Math	12	12	12
	HSS Electives	9	9	9
	Advanced Science	9	9	9
	Planetary Science	18	9	9
		48	39	39
Fourth Year				
	HSS Electives	9	9	9
	Planetary Science	9	9	9
	Additional Science and Engineering	9	9	9
		27	27	27

GPS Minor Requirements

The GPS minor is intended for non GPS undergraduates to supplement major degree with knowledge of earth and planetary science. Students completing the GPS minor will have the phrase “minor in Geological and Planetary Sciences” added to their transcript. Any student interested in a minor in GPS is urged to contact any option representative in the division.

1. Ge 11a and Ge 11b
2. One of Ge 11c or Ge 11d
3. 27 units of 100-level or higher GPS courses, excluding Ge 108 and Ge 109.

History Option and Minor

The history option allows students to study past societies and their development in more depth than can be done within the limits of the Institute humanities requirements. With the guidance of a faculty member in history, students taking the option explore the range of human experience, in the realms of politics, culture, religion, and economics, that lies outside the realm of science and technology. They also learn the critical reading and thinking skills, and the facility in writing, that are central to the historical enterprise. The history option thus provides students with an important supplement to the scientific training and technical skills they acquire in other courses and options. In addition, it offers excellent preparation for careers in business, administration, law, journalism, or public affairs, as well as a solid foundation for graduate work in history.

History majors must take at least 99 units of history courses (including freshman humanities) during their four years as undergraduates. Of these, 27 must be in the senior tutorial (H 99 abc).

Each history major will choose an area of concentration in consultation with his or her adviser and the history option representative. These areas might include, but are not restricted to, fields such as ancient history, medieval Europe, early-modern Europe, modern Europe, Russian history, American history pre-1865, American history post-1865, early-modern history of science, modern history of science, or economic history. He or she must take 63 units of courses in this area; 27 of these units must be in the senior tutorial H 99 abc. The senior tutorial will culminate in a research paper.

Each student must take the remaining 36 units of history required by the option in areas other than the area of concentration, again defined in consultation with his or her adviser and the history option representative. These areas may include not only fields within the discipline of history proper, but also useful cognate fields such as economics, political science, anthropology, law, English, or a foreign language.

A student considering the history option when he or she comes to Caltech will be well advised to take one course from Hum/H 1, 2, 3, or 4. In the sophomore year, the student should take upper-level history courses, but this is also a good time to pursue the study of English or philosophy, to begin or continue a foreign language, and to do introductory work in the social sciences. A student will normally make a commitment to an area of concentration early in the junior year. At the beginning of the senior year, a history major will enroll in H 99 abc with a faculty member in his or her area of concentration. The first term of this course will be devoted to preparation, the second to research, and the third to the writing of a substantial research paper.

Option Requirements
1. H 99 abc.
2. 72 additional units of history courses numbered 99 or above. Up to nine units of Hum/H 1, 2, 3, or 4 and/or up to nine units of H 98 may be substituted for up to 18 of these units.
3. 63 of the total history units, including H 99 abc, must be in an area of concentration, as defined in consultation with the student's adviser and the history option representative.
4. 36 of the total history units must be in an area or areas other than the area of concentration, as defined in consultation with the student's adviser and the history option representative. H 99 abc may not be used to fulfill this requirement.
5. 54 additional units of science, mathematics, and engineering courses. This requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by menu courses.
6. Three units of oral communication. En 84 satisfies this requirement, as do oral communication courses offered by other options.
7. Passing grades must be earned in a total of 486 units, including the courses listed above.

History Minor Requirements
The history minor is designed for students who want to pursue concentrated study in history without the extensive course work and the senior thesis required by the history option.

History minors must take 72 units of history courses. These units may include one freshman humanities course; they may also include one directed reading course (H 98). Students wishing to do a minor in history must declare a minor with the history option representative. Students completing the history minor requirements will have the phrase "minor in history" added to their transcripts.
1. 72 units of history courses numbered 99 or above.
2. Nine units of Hum/H 1, 2, 3, or 4 may be substituted for any nine of the 72 units required for the minor.
3. Nine units of H 98 may be substituted for any nine of the 72 units required for the minor.

History and Philosophy of Science Option and Minor

The option in history and philosophy of science (HPS) provides students with a broad education in the historical and philosophical issues arising in connection with science and technology. Students take courses addressing fundamental questions about scientific concepts and practice, such as the following: To what extent was the scientific revolution revolutionary? What is a scientific explanation and how do scientists go about constructing and justifying one? How have conceptions of scientific experimentation changed over time? How and why did modern physics (or chemistry or biology) emerge in the form that it did? How should the theory of evolution inform our conception of the modern mind and brain? What role can the neurosciences be expected to play in solving the "mind-body" problem? The option thus aims to give students a broad basic understanding of the ways in which science is practiced and the ways in which that practice has changed over time. It is designed to complement the regular curriculum at Caltech, offering students the opportunity to enlarge upon and to contextualize the strong technical skills they acquire in other courses and options.

The HPS option provides excellent preparation for students going into law, business, medicine, and public affairs, as well as solid preparation for graduate work in the history and/or philosophy of science. In addition, and because of its emphasis on essay writing and the formulation of complex philosophical and historical arguments, it aids budding scientists and engineers in developing the writing and communication skills that are increasingly vital today.

Option Requirements

1. Hum/H/HPS 10, HPS 102 ab, HPS/Pl 120, and HPS 103 (normally for 9 quarters). HPS 102 b fulfills the Institute scientific writing requirement.
2. Three advanced courses in the history of science, chosen from HPS/H offerings with a course number of 98 or higher (see note 2).
3. Three advanced courses in philosophy of science, chosen from HPS/Pl offerings with a course number of 98 or higher (see note 2).
4. 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.
5. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Explanatory Notes

1. It is desirable that students enter the option in their sophomore year. However, students may also enter the option in their

junior year if they can complete the option's requirements in time for graduation.
2. No more than nine units of HPS 98 may be counted toward the HPS major.

Typical Course Schedule

First Year

It is recommended that students intending to follow the HPS option take Hum/H/HPS 10 as one of their freshman humanities courses. Students making the decision to take this option in their sophomore year should take Hum/H/HPS 10 and HPS/Pl 120 as early as possible in that year.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
HPS 10[1]	Introduction to History of Science	9	-	-
HPS/Pl 120[1]	Introduction to Philosophy of Science	-	9	-
	Advanced HPS/History	-	-	9
HPS 103	Public Lecture Series	1	1	1
	Menu Course	-	-	9
Ec 11	Introductory Social Science			
or PS 12		9	-	-
	Other Electives	9	18	27
		46	46	46
Third Year				
HPS 103	Public Lecture Series	1	1	1
	Advanced HPS/History	-	9	9
	Advanced HPS/Philosophy	9	9	9
	Science, Math, Engineering	9	9	9
	Advanced Social Science[2]	9	-	-
	Other Electives	18	18	18
		46	46	46
Fourth Year				
HPS 103	Public Lecture Series	1	1	1
HPS 102 ab[3]	Senior Research Seminar	-	12	12
	Advanced Social Science[2]	9	-	-
	Science, Math, Engineering	9	9	9
	Other Electives	27	18	18
		46	40	40

Note: *Not all required courses are offered each term; students should consult the current Catalog to determine which terms required courses are being offered, and should construct their course plan for the year accordingly.*

[1] *If not taken in first year, otherwise one additional HPS or elective.*

[2] *It is recommended that students choose their advanced social science electives from among courses that will enlarge their perspective on topics related to HPS (e.g., Ec/SS 129, Ec/SS 130, Psy 101, Psy 125, Psy/CNS 130, PS 120, PS 121, PS 122, An 22).*

[3] *HPS 102 ab may be taken in any two consecutive terms in the senior year. Students should coordinate with their HPS adviser to determine their course schedule.*

History and Philosophy of Science Minor Requirements

The minor in history and philosophy of science (HPS) is designed for students who want to pursue concentrated study in HPS without the extensive course work and the senior thesis required by the HPS option.

HPS minors must complete 72 units of HPS courses. These may include Hum/H/HPS 10 and up to nine units of advanced reading in HPS (HPS 98). Freshman humanities courses other than Hum/H/HPS 10 may not be counted toward an HPS minor. Students wishing to do a minor in HPS must declare a minor with the HPS option representative. Those completing the HPS minor requirements will have the phrase “minor in history and philosophy of science” added to their transcripts.

1. 72 units of HPS courses numbered 99 or above.
2. Nine units of HPS 98 may be substituted for any nine of the 72 units required for the minor.
3. Nine units of Hum/H/HPS 10 may be substituted for any nine of the 72 units required for the minor.

Independent Studies Program

The Independent 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 independent 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 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 three advisers, two of whom must be professorial faculty. Application material may be obtained at the Registrar’s Office or from the dean of students.

Administrative Procedures and Guidelines

1. An interested student must recruit three individuals, representing at least two divisions of the Institute, who approve of his or her plans and agree to act as an advisory “committee of three.” The committee of three forms the heart of the program and bears the chief responsibility for overseeing the student’s progress. The chair and one other member must be on the professorial staff. The third member may be any qualified individual, such as a postdoctoral fellow, graduate student, or faculty member of another institution.

2. The student must submit a written proposal to the dean of students, endorsed by the committee of three, describing his or her goals, reasons for applying, and plan of study for at least the next year. If persuaded that the proposal is sound and workable, the dean endorses it and passes it on to the Curriculum Committee. This committee, in turn, reviews the proposal and, if it is acceptable, assumes responsibility for oversight of the program.
3. To implement the program, a written contract is now drawn up between the student, the committee of three, and the Curriculum Committee. 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 three 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 three, 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.

Mathematics Option

The four-year undergraduate program in mathematics leads to the degree of Bachelor of Science. The purpose of the undergraduate option is to give students an understanding of the broad outlines of modern mathematics, to stimulate their interest in research, and to prepare them for later work, either in pure mathematics or allied sciences. Unless students have done very well in mathematics courses in their freshman and sophomore years, they should not contemplate specializing in mathematics.

Since the more interesting academic and industrial positions open to mathematicians require training beyond a bachelor's degree, students who intend to make mathematics their profession must normally plan to continue with graduate study. Some students use their background in mathematics as an entry to other fields such as physics, computer science, statistics, economics, business, finance, medicine, or law.

The schedule of courses in the undergraduate mathematics option is flexible. It enables students to adapt their programs to their needs and mathematical interests and gives them the opportunity to become familiar with creative mathematics early in their careers. In particular, students are encouraged to consider courses in areas such as applied and computational mathematics, physics, finance, economics, control and dynamical systems, computer science, electrical engineering, and computation and neural systems.

During each term of their junior and senior years, students normally take 18 units of courses in mathematics or applied and computational mathematics, including the required courses Ma 108 abc and 109 abc. Any course listed under applied and computational mathematics is regarded as an elective in mathematics and not as an elective in science, engineering, or humanities. Those who have not taken Ma 5 as sophomores must do so as juniors. Overloads in course work are strongly discouraged; students are advised instead to deepen and supplement their course work by independent reading.

A student whose grade-point average is less than 1.9 at the end of the academic year in the subjects under mathematics and applied and computational mathematics may, at the discretion of the department, be refused permission to continue work in the mathematics option.

Option Requirements

1. Ma 5 abc, Ma 10, Ma 108 abc, Ma 109 abc.
2. Ma/CS 6 a or Ma 121 a.
3. Ma/CS 6 c or Ma 116 a or Ma/CS 117 a.
4. 45 additional units in Ma or ACM numbered 90 or above (other than Ma 98). Courses in other options with high mathematical content may be used to fulfill this requirement with the approval of the executive officer for mathematics. Of these 45 units, at most 18 can be in ACM or other courses outside Ma.
5. Math majors must take two quarters (18 units) of a single course, chosen from the Ma course listings with numbers between 110 and 190, inclusive. (In years where one of these courses is given as a one-term course only, it cannot be used to satisfy this requirement.) These two quarters may be used to meet requirements 2, 3, or 4.
6. Unlike courses satisfying requirements 4 and 5, which may be

taken pass/fail, none of the courses satisfying requirements 1–3 may be taken on a pass/fail basis.

7. Passing grades must be earned in a total of 486 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
Ma 5 abc	Introduction to Abstract Algebra	9	9	9
	HSS Electives	9	9	9
	Electives[1]	9	9	27
		45	45	45
Third Year				
Ma 10	Oral Presentation	3	-	-
Ma 108 abc	Classical Analysis	9	9	9
Ma/CS 6 ac	Introduction to Discrete Mathematics	9	-	9
	HSS Electives	9	9	9
	Electives[1]	18	27	18
		48	45	45
Fourth Year				
Ma 109 abc	Introduction to Geometry and Topology	9	9	9
	HSS Electives	9	9	9
	Electives[1]	27	27	27
		45	45	45

[1] *Includes menu course (second year, if not taken in freshman year). Also must include courses to meet option requirements 4, 5.*

Mechanical Engineering Option

The objective of the undergraduate program in mechanical engineering at Caltech is to prepare and inspire students for careers that lead to top positions in academia, industry, and government in areas related to fluid, solid, thermal, and mechanical systems. Specifically, the objective is to prepare students for graduate school and for professional practice in an era of rapidly advancing interdisciplinary technology.

To attain these objectives, 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 implications of engineering developments, including societal, cultural, and environmental impacts.

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 of the traditional disciplines. Examples of the new disciplines include micro- and nanomechanical 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.

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. Beyond the Institute-wide requirements of physics, mathematics, and humanities, these programs require one year of applied and computational mathematics and additional course requirements listed below.

A student whose interests relate to mechanical engineering, but who wishes to pursue a broader course of study than that allowed by the requirements below, may elect the engineering and applied science option.

Attention is called to the fact that any student whose grade-point average is less than 1.9 at the end of the academic year in the required courses listed below may be refused permission to continue work in this option.

Option Requirements

1. E 10, E 11.
2. ACM 95 abc or ACM 101 abc.
3. 9 units from ACM 11, CS 1, CS 2, CS 11, EE/CS 51, Ph 20–22.
4. ME 35 abc, 18 ab, 19 ab, 71, 65 or MS 115 b, and CDS 110 a.
5. 9 units of ME 96 and 9 units of additional engineering laboratory[1] (such as CS/EE/ME 75 abc, MS 90, ME 72 b), or an experimental senior thesis (ME 90 abc).
6. In addition to the above courses, 27 units selected from Ae/APh/CE/ME 101 abc, Ae/AM/CE/ME 102 abc, Ae/ME 120 ab, AM/CE 151 ab, CDS 110 b, CDS 140, EE/BE 185, E/ME 103, E/ME 105, ME 20, 66, 72 a (only if ME 72 b is completed), 90 abc, 91 abc, 115 ab, 118, 119 ab, 171, MS 115 a, or an advanced engineering course approved in advance by the mechanical engineering faculty.
7. A design project. This requirement may be fulfilled by taking one of the following: ME 72 ab, E/ME 105, CS/EE/ME 75 abc. When appropriate, students may also seek consent from the ME undergraduate option representative and the student's adviser to fulfill this requirement by taking ME 90 abc, ME 91 abc, or another suitable project course. If ME 72, CS/EE/ME 75 abc, or ME 90 is chosen, these units may also be used to fulfill requirement 5.
8. None of the courses satisfying requirements 2 through 7 may be taken pass/fail.
9. Passing grades must be earned in a total of 486 units, including courses listed above.

[1] *Excluding courses for which freshman laboratory credit is allowed.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics	9	9	-
Ph 2 ab	Sophomore Physics	9	9	-
	HSS Electives	9	9	9
	Menu class	-	-	9
ME 35 abc	Statics and Dynamics	9	9	9
ME 18 ab	Thermodynamics	-	9	9
ME 71	Introduction to Engineering Design	-	-	9
		36	45	45

Third Year				
ACM 95 abc	Intro. Methods of Applied Math.	12	12	12
ME 19 ab	Fluid Mechanics	9	9	-
	HSS Electives	9	9	9
	Elective	-	9	9
	Laboratory	-	-	9
E 10	Technical Seminar Presentation	3	-	-
E 11	Written Technical Communication	3	-	-
		36	39	39

Fourth Year				
ME 65	Mechanics of Materials	9	-	-
CDS 110 a	Introductory Control Theory	12	-	-
ME 96	Mechanical Engineering Lab	-	-	9
	HSS Electives	9	9	9
	ME Electives	9	9	-
	Electives	9	18	18
		48	36	36

Suggested Electives
Elective courses for the third and fourth year should be selected in consultation with the student's faculty adviser to pursue an interdisciplinary topic or a specialization of interest to the student. Such specializations include micro- or nanomechanical systems, simulation and synthesis, integrated complex distributed systems, kinematics, dynamics, fluid mechanics, solid mechanics, mechanical systems, control systems, engineering design, thermal systems, energy systems, combustion, or biological engineering.

Philosophy Option and Minor

The philosophy option provides students with a broad education in philosophy. The courses in the philosophy option concentrate in four major areas: philosophy of science; philosophy of mind, brain, and behavior; history of philosophy; and moral and political philosophy. The option is designed to complement the scientific curriculum at Caltech, to provide students with new perspectives on the material they learn in their science courses, and to enable them to bring their technical skills and scientific learning to traditional problems in philosophy. In addition, the philosophy option focuses on the development of rigor in argument, as well as clarity in written and oral communication.The philosophy curriculum will provide interested students with a solid foundation for graduate work in philosophy. In addition, the analytical and communication skills learned in the philosophy option provide an excellent foundation for careers in law, business, medicine, and scientific research.

Philosophy majors must take at least 99 units of philosophy courses during their four years as undergraduates. These must include 18 units of Pl 90 ab, to be taken in any two consecutive terms in the senior year. The 99 units may include nine units of either Hum/Pl 8 or Hum/Pl 9, nine units of Pl 98, and up to 18 units of study in related disciplines.

Depending on their interests, philosophy majors may be required by the option representative or their advisers to take up to 18 units in one or more related areas. For example, students writing on political philosophy or philosophy of neuroscience will be expected to have the appropriate political science or neuroscience background. Students whose primary interest lies in the philosophy of science—particularly in the philosophy of particular sciences such as physics or biology—will have their intellectual interests best served by taking classes in both the history and philosophy of science. Such students are encouraged to pursue the HPS option; or, if they choose the philosophy option, they may be required to take some history of science courses toward their 99-unit requirement.

Students considering the philosophy option will be well advised to take either Hum/Pl 8 or Hum/Pl 9 as one of their freshman humanities courses. From the sophomore year onward, they should plan on taking one philosophy course per term, culminating in two terms of Pl 90 ab in the senior year. Students in Pl 90 ab work with a faculty adviser to write a 10,000–12,000 word paper on a topic of mutual interest. Senior theses are expected to be of a high standard and to form the basis of students' applications to graduate study in philosophy, should they so desire.

Option Requirements

1. Pl 90 ab.
2. 63 units of advanced philosophy courses, numbered 99 or above. (Up to nine units of Hum/Pl 8 or Hum/Pl 9 and/or up to nine units of Pl 98 may be substituted for up to 18 of these advanced units.)
3. 18 units of advanced philosophy courses numbered 99 or above, or advanced non-philosophy courses that are closely related to the student's area(s) of philosophical interest. (Students wishing to count non-philosophy courses toward their option requirements must obtain prior approval from the philosophy option representative or their adviser. Students will normally not be permitted to satisfy this requirement with core courses.)
4. 54 units of science, mathematics, and engineering courses in addition to the core. This requirement cannot be satisfied by core or menu courses, or by courses listed as satisfying the introductory laboratory requirement. Students are strongly encouraged to choose their additional courses in areas that complement their philosophy studies.
5. Passing grades must be earned in a total of 486 units, including the courses listed above.

Philosophy Minor Requirements

The minor in philosophy is designed for students who want to pursue concentrated study in philosophy without the extensive course work and the senior thesis required by the philosophy option.

Philosophy minors must complete 72 units of philosophy courses. These units may include nine units of Hum/Pl 8 or Hum/Pl 9 and/or nine units of reading in philosophy (Pl 98). Students wishing to do a minor in philosophy must declare a minor with the philosophy option representative. Students completing the philosophy minor requirements will have the phrase "minor in philosophy" added to their transcripts.

1. 72 units of philosophy courses numbered 99 or above.
2. Nine units of Pl 98 may be substituted for any nine units of the 72 required for the minor.
3. Nine units of either Hum/Pl 8 or Hum/Pl 9 (not both) may be substituted for any nine units of the 72 required for the minor.

Physics Option

The physics option offers instruction in the fundamentals of modern physics and provides a foundation for graduate study, which is generally necessary for a career in basic research. Many individuals have also found that the physics program forms an excellent basis for future work in a variety of allied fields.

While all Caltech students must take the five terms of introductory courses, an intensive version of the sophomore course (waves, quantum mechanics, and statistical mechanics) is offered for those planning further study in physics. The required junior-level courses give a thorough treatment of fundamental principles. Elective courses taken during the junior and senior years allow students to explore their particular interests. Some electives offer broad surveys, while others concentrate on particular fields of current research. A choice of laboratory courses is offered at several levels. Students are encouraged to become active participants in research on campus. Academic credit for physics work done outside of the classroom can be awarded in a variety of ways.

Students must maintain a grade-point average of 1.9 or better each year in the subjects listed under this division to remain in the physics option.

Option Requirements

The first three 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.
2. Ph 6[1] or APh 24.

3. Ph 7.
4. 27 units of Ph 78, or 18 units of Ph 77, or 9 units of Ph 77 and 9 units from APh 77 or Ay 105.
5. Ph 70[2].
6. Ph 106.
7. Ph 125.

[1] *Some laboratory courses from other options have considerable physics content, and students wishing to satisfy this requirement with such a course may petition the Physics Undergraduate Committee for approval.*
[2] *Other communication courses (e.g., E 10, Ay 30, Ma 10) may be substituted for Ph 70.*

Required Electives

1. 90 units, in addition to the above, of any of the following: any Ph, Ay, or APh course numbered 100 or above, or any of Ph 5, Ph 78, Ph 79, ACM 95, ACM 101, Ma 5, Ma 108, up to 12 units of Ph 20–22, or up to 10 units of Ay 20–21. 9 units toward the 90-unit requirement will be given for taking three terms of Ph 77. Students are encouraged to take ACM 95 as part of this requirement. The pass/fail option cannot be exercised on any courses used for this requirement, with the exception of ACM 95. No more than 9 units of Ph 171–173 may apply toward this requirement without permission from the Physics Undergraduate Committee. In individual cases, this committee may allow other courses with substantial physics content to apply toward the requirement; seniors must submit their petitions for this purpose before the first day of third term.
2. 9 units of science or engineering electives outside of Ph, APh, Ma, and ACM. These units are in addition to the required Core Science Electives.
3. Passing grades must be earned in a total of 486 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 12	Waves, Quantum Physics, and Statistical Mechanics	9	9	9
Ma 2 ab	Sophomore Mathematics	9	9	-
	HSS and/or PE Electives	15	9	9
	Physics Laboratory	0	9	9
ACM 95 abc	Intro. Methods of Applied Math.	12	12	12
	Core Science Elective	-	-	9
		45	48	48

Third Year				
Ph 106 abc	Topics in Classical Physics	9	9	9
Ph 125 abc	Quantum Mechanics	9	9	9
	HSS and/or PE Electives	9	9	9
	Electives	18	18	18
		45	45	45
Fourth Year				
Ph 77 abc	Advanced Physics Laboratory	9	9	-
Ph 70	Oral and Written Communication	-	6	-
	Advanced Physics Electives	18	18	18
	Electives	9	6	18
	HSS and/or PE Electives	9	9	9
		45	48	45

Political Science Option

The political science option provides students with training in the substance and methods of modern political science, including the analysis of representative democracy, electoral institutions, the allocation of public goods, and regulatory behavior. The option emphasizes formal tools like game theory, social choice theory, and formal political theory along with quantitative methodologies to test those theories. In addition, the option encourages original research. The design of the political science option insures that students will be well suited to pursue careers in government or the private sector, as well as to pursue graduate work in political science.

Option Requirements

1. PS 12, PS 132, Ec 122.
2. Four political science courses from the list: PS 120, 123, 126, 130, 135, PS/SS 139, PS 141, Law/PS/H 148 ab, PS/Ec 172.
3. PS 99 ab.
4. 36 additional units in advanced political science, economics, law, social science, psychology, or history.
5. 36 additional units in advanced social science, science, engineering, or mathematics.
6. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
PS 12	Introduction to Political Science	9	-	-
PS 132	Formal Theories in Political Science	-	9	-
Ec 122	Econometrics	-	9	-
	Electives	36	27	45
		45	45	45

Third Year				
	Political Science Electives[1]	18	18	18
	Electives	27	27	27
		45	45	45
Fourth Year				
PS 99 ab	Research in Political Science	-	9	9
	Political Science Electives[1]	18	18	18
	Electives	27	18	18
		45	45	45

[1] *See option requirements 2, 4, 5.*

Structural Mechanics Minor

This minor is intended to supplement one of Caltech's undergraduate degrees and is designed for students who wish to broaden their knowledge beyond their normal major, especially for those who wish to join the structural engineering profession after graduation or pursue a graduate degree in structural mechanics or structural engineering. Students completing the structural mechanics minor requirements will have the phrase "minor in structural mechanics" added to their academic transcripts.

Minor Requirements

The student must complete 54 units of classes selected from Ae/AM/CE 102 abc, AM/CE 151 ab and CE 160 ab, and obtain a grade of B- or higher. Courses taken as part of the structural mechanics minor are counted toward the total 486-unit Institute graduation requirement.

Section Four

Information for Graduate Students

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The Institute offers graduate work leading to the degrees of Master of Science and Doctor of Philosophy. In addition, it offers the following intermediate degrees: Aerospace Engineer, Civil Engineer, Electrical Engineer, and Mechanical Engineer.

The academic work of the Institute is organized into six divisions: Biology; Chemistry and Chemical Engineering; Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics and Astronomy.

Graduate work at the Institute is further organized into graduate options, which are supervised by those professors whose interests and research are closely related to the area of the option, within the administrative jurisdiction of one or more of the divisions. The graduate student working for an advanced degree in one of the graduate options is associated with an informal group of those professors who govern the option, other faculty including research associates and fellows, and other graduate students working for similar degrees.

A faculty member serves as the representative for an option. The option representative provides consultation on academic programs, degree requirements, financial aid, etc., and provides general supervision to graduate students in the option. The Committee on Graduate Studies, which includes the option representatives, elected members of the faculty at large, and graduate students appointed by the Graduate Student Council, exercises supervision over the scholastic requirements established by the faculty for all advanced degrees, provides policy guidance to the dean of graduate studies, and certifies all candidates for graduate degrees to the faculty for their approval. The option representatives for 2009–10 are as follows:

Aerospace	Prof. D. Meiron
Applied and Computational Mathematics	Prof. T. Hou
Applied Mechanics	Profs. N. Lapusta and T. Heaton
Applied Physics	Prof. S. Troian
Astrophysics	Prof. G. Djorgovski
Behavioral and Social Neuroscience	Prof. R. Kiewiet
Biochemistry and Molecular Biophysics	Prof. R. Phillips
Bioengineering	Prof. N. Pierce
Biology	Prof. B. Hay
Chemical Engineering	Prof. K. Giapis
Chemistry	Prof. D. Dougherty
Civil Engineering	Profs. N. Lapusta and T. Heaton
Computation and Neural Systems	Prof. S. Shimojo
Computer Science	Prof. M. Desbrun
Control and Dynamical Systems	Prof. J. Marsden
Electrical Engineering	Prof. A. Hajimiri
Environmental Science and Engineering	Prof. P. Wennberg

Geological and Planetary Sciences	Prof. R. Clayton
Materials Science	Prof. B. Fultz
Mathematics	Prof. A. Borodin
Mechanical Engineering	Profs. N. Lapusta and T. Heaton
Physics	Prof. F. Porter
Social Science	Prof. R. Kiewiet

GRADUATE POLICIES AND PROCEDURES

Admission to Graduate Standing

Application

An application for admission can be completed electronically at http://www.gradoffice.caltech.edu. Admission will be granted *only to a limited number of students of superior ability*, and application should be made as early as possible. In general, admission to graduate standing is effective for enrollment only at the beginning of the next academic year. The California Institute of Technology encourages applications from members of groups underrepresented in science and engineering, including women. Applicants will automatically be considered for financial aid; no additional application is required. Completed applications are due in the Graduate Office no later than January 15; January 1 for applied mechanics, biochemistry and molecular biophysics, bioengineering, biology, chemistry, civil engineering, computer science, environmental science and engineering, geological and planetary sciences, mechanical engineering, and physics; December 15 for social science. Some options will review an application received after the deadline, but that applicant may be at a disadvantage in the allocation of financial assistance or in the priority for admission.

To be admitted to graduate standing an applicant must in general have received a bachelor's degree representing the completion of an undergraduate course in science or engineering equivalent to one of the options offered by the Institute. He or she must, moreover, have attained such a scholastic record and present such recommendations as to indicate fitness to pursue, with distinction, advanced study and research. Admission sometimes may have to be refused solely on the basis of limited facilities in the option concerned.

Required Tests

The verbal, quantitative, and analytical components of the Graduate Record Examination are required by all graduate options, and subject scores are required by most options as part of the application for graduate admission.

International Students
In order to be admitted for graduate study, students from non-English-speaking countries are expected to read, write, and speak English and comprehend the spoken language. Although not *required* for admission, it is important to demonstrate a strong capability in English prior to admission to Caltech, as it is one of the criteria for admission and financial aid. In addition, to be a candidate for an advanced degree, the student must have acquired the power of clear and forceful self-expression in both oral and written English.

Applicants whose first or native language is not English are required to take a test of English proficiency as part of the application procedure. These tests are given at centers throughout the world, on several dates each year. Caltech recognizes scores from the Educational Testing Service (ETS) and from the Cambridge Examinations and the International English Language Testing System (IELTS). In addition, applicants who are taking the TOEFL exam are highly encouraged to take the Test of Written English (TWE) and the Test of Spoken English (TSE) and submit these scores as part of their application. Applicants should arrange for the results of these tests to be sent to the Office of the Dean of Graduate Studies prior to the application deadline (institutional code 4034).

The testing schedules for and information on the TOEFL, TWE, and TSE may be obtained by writing to TOEFL, Educational Testing Service, Princeton, NJ 08540. They are also available online at http://www.toefl.org.

The testing schedules for and information on the IELTS exam may be obtained by writing to The British Council, Bridgewater House, 58 Whitworth Street, Manchester M1 6BB, United Kingdom. They are also available online at http://www.ielts.org.

It is strongly recommended that students who do not achieve a high score on these tests, or who have little opportunity to communicate in English, make arrangements for intensive work during the summer preceding their registration. All international students are tested upon arrival at Caltech and, if found to be seriously deficient in their ability to communicate in English, must take special courses in English as a Second Language (ESL).

Special Students
Students who hold a bachelor's degree or the equivalent may in exceptional cases be admitted, for a period of up to one year, as special graduate students to carry out full-time studies at the Institute without being candidates for a degree from Caltech. Special students must be registered for a minimum of 36 units each term and may enroll in either research and/or courses to fulfill requirements. 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. Registration as a special graduate student does not count toward minimum residency requirements for an advanced degree.

This status is ordinarily restricted to students who are registered in, or are on sabbatical from, an advanced degree program at another institution and who need to make use of resources available at Caltech. Admission to such status requires sponsorship by a Caltech faculty member. Application should be made directly to the dean of graduate studies, following the same procedures as for regular graduate students.

Visiting Student Researchers

In exceptional cases, students from other universities may visit Caltech to carry out research under the direction of a Caltech faculty member. Students must be registered in and pay tuition at another institution, and be on sabbatical or leave, to qualify for this status. These students will receive the status of a visiting student researcher at Caltech and will not be eligible to receive any funding from the Institute. This status is restricted to students who will not be enrolled at Caltech, but will conduct research at the Institute. (Graduate students pursuing a degree at another university may enroll in classes, receive a stipend, and pay tuition as special students at Caltech. Please see Special Students on page 239.) Applications for the visiting student researcher status must be submitted to the dean of graduate studies or dean of students along with all supporting documents and evidence of appropriate financial support (for international students). Please contact one of the deans for information on procedures and for a list of supporting documents.

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 (one academic year) of graduate work; for Aerospace Engineer, Civil Engineer, Electrical Engineer, and Mechanical Engineer, a minimum of six terms (two academic years) of graduate work; and for Doctor of Philosophy, a minimum of nine terms (three academic years) of graduate work.

Registration

Graduate students are required to register for each term of residence, whether they are attending a regular course of study, carrying on research, doing independent reading, writing a thesis, or utilizing any other academic service or campus facility.

A graduate student must be registered for 36 or more units to be classified as a full-time student, but course loads greater than 45 units are more common. International students on student visas must be registered for at least 36 units per term during their entire tenure at Caltech. A graduate student who registers for less than 36 units, or who undertakes activities related to the Institute aggregating more than 62 hours per week (in class, research, and teaching assistantship units) must receive approval from the dean of graduate studies. Petition forms for this purpose may be obtained from the Graduate Office and must carry the recommendation of the option representative of the student's major option before submission to the dean of graduate studies.

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

Before registering, students should consult with members of the option in which they are taking their major work to determine the studies that they can pursue to the best advantage. An adviser is assigned to each entering graduate student by the option representative. In most options a new adviser is assigned when the student begins research. Only members of the professorial faculty may serve as advisers. With the approval of the dean of graduate studies, any graduate student whose work is not satisfactory may be refused registration at the beginning of any term by the division in which the student is doing his or her major work.

In registering for research, students should indicate the name of the instructor in charge, and should consult with him or her to determine the number of units to which the proposed work corresponds. At the end of the term, the instructor in charge may decrease the number of units for which credit is given if he or she feels that the progress of the research does not justify the full number originally registered for.

Students will not receive credit for courses unless they are properly registered. The students themselves are charged with the responsibility of making certain that all grades to which they are entitled have been recorded.

All changes in registration must be reported, on drop or add cards, to the Registrar's Office by the student. Such changes are governed by the last dates for adding or dropping courses as shown on the academic calendar on pages 4 and 5. A student may not withdraw from or add a course after the last date for dropping or adding courses without his or her option's consent 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, predoctoral students are strongly encouraged to continue their research throughout the summer quarter. They are entitled to at least two weeks' annual vacation (in addition to Institute holidays), but 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, 36 units must be taken in the summer quarter.

Sabbatical

Graduate students are required to maintain their admission status until all requirements for a degree are fulfilled, whether by continuity of registration or on the basis of an approved sabbatical. A sabbatical for medical or other reasons may be approved for up to one year at a time. A sabbatical will be approved to meet military obligations, and tuition adjustments will be made if the sabbatical must be initiated within a term (see pages 147–149). An approved sabbatical indicates that the student can return to the option at the end of the sabbatical. A sabbatical for medical reasons requires a petition to the dean of graduate studies, supported by a physician, prior to reinstatement. Financial aid awarded by the Institute will not be deferred from the term for which it was originally offered and must be requested again for the term of reenrollment.

In general, international students cannot take a sabbatical without jeopardizing their visa status. Students who hold nonimmigrant visas must meet with an adviser in the International Student Programs Office to determine the impact that a sabbatical will have on their immigration status.

Detached duty status continues registration for a student doing research at another location, such as a national facility, for an extended period. Reduced duty status continues registration for a student who cannot carry a full load due to medical disability, including pregnancy.

Graduate students who become pregnant during their studies must be provided a minimum of six weeks of paid leave with full benefits and another six weeks of family bonding leave without pay but maintaining full benefits. Family bonding leave without pay is available to the father, if the father is a graduate student at Caltech.

The paid and unpaid leaves are intended to cover normal pregnancy and childbirth. If a longer leave is required due to medical complications, a six-month extension of leave beyond the 12 weeks may be taken as a medical leave with approval of the dean of graduate studies.

Petition forms for an approved sabbatical, or detached or reduced duty status, may be obtained from the Graduate Office and must, before submission to the dean of graduate studies, carry the recommendations of the student's option representative and, where appropriate, the thesis adviser. In case of a lapse in admission status, readmission must be sought before academic work may be resumed or requirements for the degree completed. Registration is required for the quarter in which the thesis defense is undertaken, with the exception of the first week of each quarter, but is not normally allowed beyond the last date of the quarter. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms following the thesis defense.

The dean of graduate studies may place a graduate student on involuntary sabbatical if persuaded by the evidence that such an action is necessary for the protection of the Institute community or for the personal safety or welfare of the student involved. Such a decision by the dean is subject to automatic review within seven days by the vice president for student affairs.

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 of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

The graduate student–faculty adviser relationship should be guided by norms of fairness and professionalism. Both faculty and graduate students should avoid relationships that conflict with their respective roles and duties at Caltech. Both are bound by the prevailing policies prohibiting discrimination and harassment (pages 61–62 and 68–77). 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), the dean of graduate studies, the assistant vice president for student affairs, or the office of International Student Programs. At any time a student may request that discussions remain confidential. For more details about sources of assistance, consult the graduate option regulations (pages 264–339) and the Student Grievance Procedure (page 49).

Part-Time Programs

Part-time graduate study programs at the Institute are for graduate students who cannot devote full time to their studies and are allowed to register only under special arrangements with a sponsoring organization, and such students are subject to the following rules:

Degree Programs

- Applicants for the part-time program must submit a regular application form accompanied by a detailed plan for meeting the course requirements for the degree.
- Any research work done for academic credit shall be supervised by a Caltech faculty member.
- In general, students admitted to the part-time program are required to take at least 27 units of graduate course work or research work each term during the first academic year.
- Any option at the Institute retains the right to not participate in the program or to accept it under more stringent conditions.

Nondegree Programs

Caltech employees, both campus and JPL, are eligible to apply to take one or more graduate courses for credit. Participants in this program will not be considered to be working toward a Caltech degree, in contrast to the part-time program for graduate degrees described above, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree.

At least one month prior to the start of the term, the employee should have an initial discussion with the option representative of the option in which the course is to be taken. Application should be made to the Graduate Office by completing the special form provided for this purpose, and providing a transcript of academic work and one letter of recommendation. The employee must meet the prerequisites for the course, and must obtain the written permission of the instructor. Individual options may require further information such as GRE scores. The decision on admission to take each course will be made by the course instructor and the option representative, with final approval by the dean of graduate studies. Taking an additional course at a later time will require full reapplication. It is the employee's responsibility to arrange a revised work schedule with the appropriate supervisor. Approval of the employee's supervisor is required.

Part-time nondegree students are subject to the Honor System (see page 32) and are under the purview of the dean of graduate studies. They may take only courses numbered 100 or higher. Research courses are excluded from the program. For courses in which a letter grade is offered, these students may not register to receive a pass/fail grade in the course, nor can credit for the course be obtained by examination. The option may limit the number of nondegree students admitted to any one course.

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, and the laboratory involved commits support for the duration of the thesis research, and provided that all Caltech graduate thesis research carried out at a special laboratory is under the supervision of Caltech faculty members.
- A student's request to carry out thesis work at a special laboratory should be formally endorsed by the appropriate committee of his or her option and by the special laboratory, on a petition submitted through the option representative to the dean of graduate studies. The special laboratory should recognize its commitment of special equipment or any other resources required for the thesis work. Approval by the special laboratory should also indicate that the thesis topic is a sensible one, and that it is not likely to be preempted by the laboratory.
- A student may take similar advantage of unique opportunities at a corporate or governmental research and development facility under the same conditions, providing that there exists a formal written agreement between the R&D facility and the student's thesis adviser, and that advance written approval is obtained from the dean of graduate studies. Such curricular practical training may in some cases involve full-time 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 doctoral dissertation. Typically, such students who

are not in a local laboratory are placed on detached duty status.

- Employment by a special laboratory of a graduate student for work not connected with his or her thesis should be regarded as equivalent to other outside employment.

Exchange Program with Scripps Institution of Oceanography

An exchange program has been established with the Scripps Institution of Oceanography (SIO), University of California, San Diego, permitting Caltech graduate students to enroll in and receive credit for graduate courses offered by SIO. Arrangements should be made through the student's major option and the Office of the Dean of Graduate Studies. The student must obtain the advance approval of the instructors of courses to be taken at SIO. In some cases, when it is in the best interests of the student, arrangements may be made for the student to be temporarily in full-time residence at SIO.

Thesis research done partly at SIO may be arranged directly by the student's option and the staff of appropriate research 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 his or her Caltech thesis adviser and will enroll for Caltech research units.

GENERAL REQUIREMENTS FOR GRADUATE DEGREES

Degree of Master of Science

The Master of Science degree is a professional degree designed to prepare a student for teaching, for further graduate studies, or for more advanced work in industry. Detailed requirements are based primarily on professional studies, and the program should be planned in consultation with the faculty in the appropriate discipline. Under normal circumstances, the requirements for the M.S. degree can be completed in one academic year.

A student who enters the Institute holding a master's degree from another institution will not normally be awarded a master's degree in the same field from the Institute unless the initial admission to Caltech graduate standing indicated that the student was to be a master's candidate. A student may not normally be awarded two master's degrees from the Institute.

Special regulations for the master's degree are listed under each graduate option. Several options do not offer an M.S. degree except in special circumstances.

Residence and Units of Graduate Work Required. At least one academic year of residence at the Institute and 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. Courses used to fulfill requirements for the bachelor's degree may not be counted as graduate residence.

To qualify for a master's degree, a student must complete the work indicated in the section on special regulations for his or her option with a grade-point average for the approved M.S. candidacy courses of at least 1.9.

In special cases, with the approval of the instructor 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.

Joint B.S./M.S. Degree. In exceptional cases, undergraduate students may pursue a joint B.S./M.S. program of study in some options. Several options do not allow a joint B.S./M.S. degree. Students should contact the graduate option representative to find out if the joint B.S./M.S. degree is possible in a particular option. Such students must follow the normal procedures for admission to the M.S. program in the option of their choice. Students attending courses or carrying out research toward an M.S. degree before completion of their B.S. degree requirements will be considered as undergraduate students and will not be eligible for graduate financial aid, graduate housing, or other graduate student privileges.

Admission to M.S. Candidacy. Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she should file in the Office of the Dean of Graduate Studies an application for admission to candidacy for the degree desired. On the M.S. candidacy form, the student must submit a proposed plan of study, which must have the approval of his or her option representative and, if a thesis is required, of his or her research adviser. Some options require a thesis or research report in addition to course requirements. The thesis or research report must be signed off on the M.S. candidacy form by the research adviser no later than two weeks before the degree is to be conferred. This approved plan of study will constitute the requirements for the degree. Any modifications must be approved by the option representative, and the initialed plan of study resubmitted to the Graduate Office at least two weeks before Commencement.

Students enrolled for the joint B.S./M.S. program must complete a minimum of 486 units for the B.S. program and 135 units for the M.S. program with no overlapping of courses.

Engineer's Degree

Engineer's degrees are awarded in aerospace, civil engineering, electrical engineering, and mechanical engineering. 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 received the master's degree and wish to pursue further studies leading toward either the engineer's or the doctor's degree must file a new petition to continue graduate work toward the desired degree. Students who have received an engineer's degree will not in general be admitted for the doctor's degree.

Residence. At least six terms of graduate residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for an engineer's degree. Of these, at least the last 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 his or her 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 his or her option when establishing a program.

Admission to Candidacy. Before the midpoint of the first term of the academic year in which the student expects to receive the degree, he or she must file in the Office of the Dean of Graduate Studies an application for admission to candidacy for the degree desired. Upon receipt of this application, the dean of graduate studies, in consultation with the chair of the appropriate division, will appoint a committee of three members of the faculty to supervise the student's work and to certify its satisfactory completion. One of the members of the committee must be in a field outside the student's major field of study. The student should then consult with this committee in planning the details of his or her work. The schedule of work as approved by the committee shall be entered on the application form and shall then constitute a requirement for the degree. Changes in the schedule will not be recognized unless initialed by the proper authority. No course that appears on the approved schedule and for which the applicant is registered may be removed after the last date for dropping courses, as listed in the *Catalog*.

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.

Students may demonstrate competence in written English by scoring 5 or above on the TWE examination or by having their final thesis accepted by the faculty. To determine oral competence in English, students from non-English-speaking countries are screened during the fall orientation session. Those who do not pass the screening must enroll in ESL 101 during the fall quarter and must subsequently score at least 50 on the standardized NTS (National Testing Service) SPEAK test. Students who score below 50 on the SPEAK test are urged to continue taking ESL classes; they must pass the SPEAK test before admission to candidacy. To help students pass this test, ESL courses are held throughout the school year and intensive English is offered in the summer. The Graduate Office will maintain a record of the test scores and will provide them to the option representatives, as needed, to verify that the student has met this requirement. (Note: Other ESL courses are open to all students who want to improve their oral skills, as described on page 446.)

Admission to candidacy must be obtained by the midpoint of the term in which the degree is to be granted.

Thesis. At least two weeks before the degree is to be conferred, each student is required to submit to the dean of graduate studies two copies of his or her thesis in accordance with the regulations that govern the preparation of doctoral dissertations. These regulations may be obtained from the Graduate Office. The candidate must obtain written approval of the thesis by the chair of the division and the members of the supervising committee, on a form obtained from the Office of the Dean of Graduate Studies.

The use of "classified" research as thesis material for any degree will not be permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

Examination. At the discretion of the option in which the degree is desired, a final examination may be required. This examination would be conducted by a committee appointed by the candidate's supervising committee.

Degree of Doctor of Philosophy

The degree of Doctor of Philosophy is conferred by the Institute primarily in recognition of breadth of scholarship, depth of research, and the power to investigate problems independently and efficiently, rather than for the completion of definite courses of study through a stated period of residence. The work for the degree must consist of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering. In addition, the candidate must have acquired the power of clear and forceful self-expression in both oral and written English.

Subject to the general supervision of the Committee on Graduate Study, the student's work for the degree of Doctor of Philosophy is specifically directed by the division in which he or she has chosen the major subject. Each student should consult his or her division concerning special divisional and option requirements.

Admission. With the approval of the dean of graduate studies, students are admitted to graduate standing by the option in which they choose their major work toward the doctor's degree. In some cases, applicants for the doctor's degree may be required to register for the master's or engineer's degree first; however, these degrees are not general prerequisites for the doctor's degree. Students who have received the master's degree and wish to pursue further studies leading toward either the engineer's or the doctor's degree must file a request to continue graduate work toward the desired degree. Students who have received an engineer's degree will not, in general, be admitted for the doctor's degree.

A student who holds a Ph.D. degree from another institution will not normally be admitted to graduate standing at Caltech to pursue a second Ph.D. degree. A student will not normally be awarded two Ph.D. degrees from the Institute.

Minor Programs of Study. The Institute does not require a minor for the Ph.D. degree, but the individual options may have minor requirements as part of their requirements for the major.

A student may undertake a minor program of study in most 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 Ph.D. diploma by the statement, "…and by additional studies constituting a minor in [name of option]."

A minor program of study should be at a level of study in the minor substantially beyond that typically acquired by students as part of their major requirements. Most options require 45 units or more, including at least one 200-level course and a coherent program of the supporting 100-level courses. The faculty of the minor option may approve a proposed minor program on the basis of overall class performance and/or by an oral examination. Detailed requirements for minor options are listed under the individual options.

Residence. At least nine terms (three academic years) of residence subsequent to a baccalaureate degree equivalent to that given by the Institute are required for the doctor's degree. Of this at least one year must be in residence at the Institute. It should be understood that these are minimum requirements, and students must usually count on spending a somewhat longer time in residence. A student whose undergraduate work has been insufficient in amount or too narrowly specialized, or whose preparation in his or her special field is inadequate, must count upon spending increased time in work for the degree.

However, no student will be allowed to continue work toward the doctor's degree for more than five academic years of graduate residence, without a petition approved by the dean of graduate studies. This petition must include a plan and schedule for completion, agreed upon and signed by the student, the research adviser, and the option representative.

Registration. Continuity of registration must be maintained until all requirements for the doctor's degree have been completed, with the exception of summer terms and authorized sabbaticals. Registration is required for the quarter in which the thesis defense is undertaken.

Admission to Candidacy. On the recommendation of the chair of the division 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 doctor's degree and has been in residence at least one term thereafter; has initiated a program of study approved by the major option and, if needed, by the minor option; has satisfied by written or oral examination the several options concerned, or otherwise shown that he or she has a comprehensive grasp of the major and minor subjects and of subjects fundamental to them; has demonstrated the ability for clear and forceful self-expression in both oral and written English; and has shown ability in carrying on research in a subject approved by the chair of the division concerned. Option regulations concerning admission to candidacy are given in a later section. Members of the Institute staff of rank higher than that of assistant professor are not admitted to candidacy for a higher degree.

Students may demonstrate competence in written English by scoring 5 or above on the TWE examination or by having their final thesis accepted by the faculty. To determine oral competence in English, students from non-English-speaking countries are screened during the fall orientation session. Those who do not pass the screening must enroll in ESL 101 during the fall quarter and must subsequently score at least 50 on the standardized NTS (National Testing Service) SPEAK Test. Students who score below 50 on the SPEAK Test are urged to continue taking ESL classes; they must pass the SPEAK Test before admission to candidacy. To help students pass this test, ESL courses are held throughout the school year and intensive English is offered in the summer. The Graduate Office will maintain a record of the test scores and will provide them to the option representatives, as needed, to verify that the student has met this requirement. (Note: Other ESL courses are open to all students who want to improve their oral skills, as described on page 446.)

A standard form, obtained from the dean of graduate studies, is provided for making application for admission to candidacy. Such admission to candidacy must be obtained before the close of the second term of the year in which the degree is to be conferred.

The student is responsible for seeing that admission is secured at the proper time. A student not admitted to candidacy before the beginning of the fourth academic year of graduate work at the Institute must petition through his or her division to the dean of graduate studies for permission to register for further work.

After achieving candidacy, each Ph.D. student should be assigned a thesis advising committee of three or more faculty members. This committee should meet informally at least once a year beginning in the fourth year of graduate study.

Candidacy (and permission to register) may be withdrawn by formal action of the option from a student whose research is not satisfactory, or for other compelling reasons. However, the option must petition through its division chair to the dean of graduate studies before taking such action.

Final Examination. Each doctoral candidate shall undergo broad oral examination on the major subject, the scope of the thesis, and its significance in relation to the major subject. The examination, subject to the approval of the dean of graduate studies, may be taken after admission to candidacy whenever the candidate is prepared; however, it must take place at least three weeks before the degree is to be conferred.

The examination may be written in part, and may be subdivided into parts or given all at one time at the discretion of the options concerned. The student must petition for this examination, on a form obtained from the Graduate Office, not less than two weeks before the date of the examination. Ordinarily, more than two weeks are needed for the necessary arrangements. An examination committee should consist of a minimum of four voting members, three of whom must be Caltech faculty. Exceptions to this rule must be approved by the dean of graduate studies in advance of the defense. 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 final form—i.e., ready for review by the dean, the members of the examining committee, and the Graduate Office proofreader.

Thesis. The candidate is to provide a copy of his or her completed thesis to the members of the examining committee at least two weeks before the final oral examination. The date of the examination and the composition of the examining committee will not be approved by the dean of graduate studies until the thesis is submitted in completed form, i.e., ready for review by the dean, the members of the examining committee, and the Graduate Office proofreader. Registration is required for the term in which the thesis defense is undertaken, but is not normally allowed beyond the last date of the term. Approval of the dean of graduate studies is required for any student seeking to enroll for subsequent terms following the thesis defense. A student may petition the dean of graduate studies for reduced tuition charges if the student supplies a copy of the thesis, schedules the examination, and submits the necessary petitions for the Ph.D. examination prior to 5:00 p.m. on the third Friday of the term in which the examination will be taken.

The last date for submission of the final, corrected thesis to the dean of graduate studies is the fifth week of the succeeding term if the candidate defended his or her thesis during the previous summer or the first or second terms; or two weeks before the degree is to be conferred if the candidate defended his or her thesis during the month of May. A final copy of the thesis is to be submitted in accordance with the regulations governing the preparation of doctoral dissertations, obtainable from the Graduate Office. In addition, it is required that all doctoral candidates submit an electronic copy of their dissertation, which the Caltech Library System will then archive and make available online, as part of the Networked Digital Library of Theses and Dissertations (NDLTD), an international organization that allows researchers to globally search a database of electronic theses and dissertations. For special option regulations concerning theses, see specific graduate options.

Before submitting the final, corrected thesis to the dean of graduate studies, the candidate must obtain approval of the thesis by the chair of his or her division and the members of the examining committee, on a form that can be obtained at the Graduate Office.

With the approval of the option concerned, a portion of the thesis may consist of one or more articles published jointly by the candidate and members of the Institute staff or other coauthors. In any case, however, a substantial portion of the thesis must be the candidate's own exposition of his or her own work.

The use of "classified" research as thesis material for any degree is not permitted. Exceptions to this rule can be made only under special circumstances, and then only when approval is given by the dean of graduate studies before the research is undertaken.

Regulations and directions for the preparation of theses may be obtained from the Office of the Dean of Graduate Studies, and should be followed carefully by the candidate.

GRADUATE EXPENSES

The tuition and fees charge for all students registering for graduate work is currently $34,437 per academic year, payable in three installments at the beginning of each term. 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 on the form available from the Graduate Office. If reduced registration is permitted, the tuition for each term is at the rate of $309 a unit for fewer than 36 units, plus $371 for fees per term, with a minimum of $1,298 per term. This tuition credit will only be made for reduced units as of the published Add Day of each term.

The payment of tuition by graduate students is required (a) without reference to the character of the work by the student, which may consist of research, independent reading, or writing a thesis or other dissertation, as well as attendance at regular classes; (b) without reference to the number of terms in which the student has already been in residence; and (c) without reference to the status of the student as an appointee of the Institute, except that members of the academic staff of rank of instructor or higher are not required to pay tuition.

Unpaid Bills. All bills owed the Institute must be paid when due. Any student whose bills are past due may be refused registration for the following term. Graduate students with a bursar's bill balance of $1,500 or more will have a hold placed on their transcripts and 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.

Information regarding fellowships, scholarships, and assistantships is discussed in the following pages. Students of high scholastic attainment may be offered special tuition awards covering all or part of the tuition fee. Loans also may be arranged by applying at the Financial Aid Office.

Caltech Card Charges. If a graduate student owes more than $1,500 at the end of the quarter, the student's ID card will be deactivated on the seventh day of the following quarter and they will be unable to charge any new purchases. Cards will be reactivated once students have paid their bill or worked out a satisfactory payment plan with the Bursar's Office.

Expense Summary 2009–10

General:	
Tuition and fees	$ 34,437.00
Other:	
Books and Supplies (approx.)	$ 1,000.00
Room:	
Avery House	
Avery House single room	$ 665.00 per month
Avery House suite room	$ 698.00 per month
Plus Avery meal plan (M–F)	$ 825.00 per term
Catalina apartments	
4 bedroom apt.	$ 525.00 per person per month
2 bedroom apt.	$ 622.00 per person per month

1 bedroom apt.	$1,077.00 per apt. per month (plus utilities)

Tuition fees for fewer than the normal number of units:

Per unit per term	$ 309.00

Contact Bursar's Office for audit fee.

Fees are subject to change at the discretion of the Institute.

Fees for Late Registration. Registration is not complete until the student has registered for a program approved by his or her adviser and has paid tuition and other fees. A penalty fee of $50 is assessed for failure to register within five days of the scheduled dates.

A $50 late penalty will be charged by the Bursar's Office for failure to clear a past-due account within five days of the beginning of instruction.

Honor System Matters. Monies owed to the Institute resulting from a Graduate Review Board decision 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 students. In addition, there are 15 spaces for graduate students in Avery House, an innovative residential community of faculty, undergraduates, and graduate students (see page 29).

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 and reservations can be obtained by writing to housing@caltech.edu or to the Housing Office, Mail Code 160-86, California Institute of Technology, Pasadena, CA 91125 or at http://www.housing.caltech.edu.

The Institute also owns a limited number of apartments and single-family houses that are available for rental, on a lease basis, to single, married, or graduate students with families. Because of limited availability, there is a waiting list for these properties. For additional information and sign-up forms, contact the Housing Office.

The Housing Office maintains a listing service of available rooms, apartments, and houses in the Pasadena area. The listings are available on the Web at http://www.housing.caltech.edu. Students preferring to live in non-Institute housing typically pay approximately $550–$600 per month in rent for a shared apartment, and somewhat more for a private apartment. Please note that the Institute cannot make negotiations for individual housing off campus.

Dining Facilities. Graduate students are granted the privilege of joining the Athenaeum (faculty club), which affords the possibility of contact with fellow graduate students and with others using the Athenaeum, including the Associates of Caltech, distinguished visitors, and members of the professional staffs of the Huntington Library and the California Institute of Technology.

The Chandler Dining Hall, located on the campus, is open Monday through Friday. Breakfast, lunch, and snacks are served cafeteria style. Café at Broad is open for lunch and dinner, Monday through Friday.

Health Services. Health services available to graduate students are explained in section one.

FINANCIAL ASSISTANCE

Caltech offers in each of its options a number of fellowships, tuition scholarships, and graduate assistantships. In general, tuition scholarships may be for full or partial tuition charges; assistantships provide stipends; and fellowships often provide both tuition scholarship awards and stipends. Graduate assistants are eligible to be considered for special tuition awards.

A request for financial assistance is included on the application for admission to graduate standing. Some options will review applications received after the deadline date, but such applicants may be at a disadvantage in the allocation of financial assistance. Appointments to fellowships, scholarships, and assistantships are decided yearly by the student's academic option.

Graduate students receiving any form of financial aid 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 research that affords them useful experience. Teaching assistantships are for up to 20 hours per week during the academic year and are devoted to preparation, grading, or consulting with students. Students may not, without advance permission from the dean of graduate studies, be a teaching assistant for a course in which they receive credit. Research assistantships are limited to less than 20 hours per week during the academic year and may be greater during the summer. Combined teaching and research assistantships are common. Stipends are based on four 12-week quarters and are paid on the first of each month. Assistantships normally permit carrying a full graduate residence schedule also. Only teaching assistants with good oral English are allowed to teach sections.

All teaching assistants are required to attend teaching-assistant training before payment can be processed. Training sessions occur during orientation week for incoming graduate students and at least once per term for continuing students, including undergraduate students with teaching responsibilities. The schedule of upcoming training sessions can be obtained from the graduate office.

Teaching assistants must familiarize themselves with Caltech's policy on harassment (see page 68). 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. Any questions should be referred to the dean of graduate studies.

Teaching and research obligations of graduate assistants shall not exceed 50 weeks per year, but may be less depending on departmental policy and the arrangements made by the adviser and the student. Graduate assistantship appointments include regular Institute holidays occurring during specified appointment periods. In addition, when necessary, graduate assistants may arrange for short-term medical disability leave (including maternity leave). Assistants should schedule their vacation and planned disability leaves with their adviser or option representative. Any questions should be referred to the dean of graduate studies.

Graduate Scholarships, Fellowships, and Research Funds

The Institute offers a number of endowed fellowships and scholarships for tuition and/or stipends to graduate students of exceptional ability who wish to pursue advanced study and research.

In addition to the National Science Foundation, the Department of Health and Human Services, the Department of Energy, the Department of Defense, NASA, and the California State Graduate Fellowship program, gifts are received from other donors to support graduate study. A number of governmental units, industrial organizations, educational foundations, and private individuals have contributed funds for the support of fundamental research related to their interests and activities. These funds offer financial assistance to selected graduate students in the form of named fellowships.

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 in the Financial Aid Office. Loans are not available to first-year international students.

Loan applicants will be asked to submit signed copies of their federal income tax returns (form 1040, 1040A, or 1040EZ), complete with all supporting schedules and attachments.

Satisfactory Academic Progress

In order to continue receiving 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 summer terms and authorized sabbaticals.

The Master of Science degree requires at least one academic year of residence at the Institute and 135 units of graduate work with a grade-point average of at least 1.9. Under normal circumstances a master's degree requires a minimum of three academic terms (one year) and 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 six terms (two years) of graduate residence are required with a minimum 1.9 overall grade-point average. The engineer's degree cannot take more than three years to complete, without a petition approved by the dean of graduate studies.

For the doctor's degree at least nine terms (three years) of residence are required, but the necessary study and research typically require more than five years. The work for the degree consists of research and the preparation of a thesis describing it, and of systematic studies of an advanced character, primarily in science or engineering. In addition, the candidate must have acquired the power of clear and forceful self-expression in both oral and written English.

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. Approval of the dean of graduate studies is required before dropping any course that brings a student below 36 units. All graduate students are expected to complete 108 units each academic year. The treatment of incomplete grades and withdrawals is specified on pages 40–41. Satisfactory academic progress is checked each academic year 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 doctoral student who has not been admitted to candidacy by the beginning of the fourth year must petition to the dean of graduate studies for permission to register for further work. In addition, no doctoral student will be allowed to register for a sixth year without approval of a petition 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 advising committee, and the option representative.

Petitions approved by the option and the dean of graduate studies reinstate student eligibility for all financial aid.

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 146–149). 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.

An overpayment or overaward occurs when a student receives more aid than he or she is eligible to receive. Therefore, the Financial Aid Office will compare actual costs to aid disbursed in accordance with federal guidelines. If aid disbursed exceeds costs, the student may be responsible for the overpayment. Any overpayment will be charged to the student on his or her student account. Additional information is available in the Financial Aid Office.

Students receiving financial aid from any source are expected to register for 36 units each term unless special arrangements have been made with the dean of graduate studies.

Charles D. Babcock Award
The Charles D. Babcock Award recognizes a student whose achievements in teaching (or other ways of assisting students) have made a significant contribution to the aeronautics department. The criteria for the award selection are as follows: The award can be made as unscheduled support for a graduate student associated with aeronautics, e.g., for travel to a technical meeting for professional advancement. All aeronautics-associated students are eligible, with preference given to those in the structures and solid mechanics group. The award may be made yearly, as merited. The timing of the award will be as special recognition warrants.

The Charles D. Babcock Award was established in 1992 in memory of Charles D. Babcock, who was professor of aeronautics and applied mechanics until 1987; he served aeronautics as option representative and the Institute as vice provost.

William F. Ballhaus Prize
A prize of $1,000 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. degree in aeronautics in 1947.

Bohnenblust Travel Grants in Mathematics
Special grants may be awarded to outstanding graduate students in mathematics to enable them to travel in the United States or abroad to further their mathematical education. The mathematics faculty established these awards in 1978 to honor H. F. Bohnenblust, who served Caltech as professor of mathematics, executive officer for mathematics, and dean of graduate studies.

Application forms and further details are available in the mathematics office, 253 Sloan.

Rolf D. Buhler Memorial Award in Aeronautics
An award of $500 is made annually to a student in the aeronautics master's program whose academic performance was exemplary and who shows high potential for future achievements at Caltech.

The Rolf D. Buhler Memorial Award in Aeronautics was established in 1990 in memory of Rolf Buhler, a 1952 graduate of GALCIT and professor of space flight at the Technical University of Stuttgart in Germany.

W. P. Carey & Co., Inc., Prizes in Applied Mathematics
Prizes of up to $1,000 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 Engineering
This prize shall be awarded each year to a candidate for the degree of Doctor of Philosophy in Mechanical Engineering whose doctoral thesis is judged to be the most original and significant by a faculty committee appointed each year by the executive officer of mechanical engineering. The prize consists of a citation and a cash award of $1,000. This prize is made possible by gifts from alumni following the mechanical engineering centennial celebrations in 2007.

Richard Bruce Chapman Memorial Award
A prize of $500 will be awarded annually to a graduate student who has distinguished himself or herself in research in the field of hydrodynamics.

Bruce Chapman was awarded an M.S. from Caltech in 1966 and a Ph.D. in 1970, both in engineering science. This award has been established in his memory by his family and friends.

Milton and Francis Clauser Doctoral Prize
An annual prize is awarded to the Ph.D. candidate whose research is judged to exhibit the greatest degree of originality as evidenced by its potential for opening up new avenues of human thought and endeavor as well as by the ingenuity with which it has been carried out. The Milton and Francis Clauser Doctoral Prize is made possible by gifts from the family and friends of these twin alumni, who received bachelor's degrees in physics in 1934, master's degrees in mechanical engineering in 1935, and doctor's degrees in aeronautics in 1937.

Donald Coles Prize in Aeronautics
The Donald Coles Prize will be awarded to the graduating Ph.D. student in aeronautics whose thesis displays the best design of an experiment or the best design for a piece of experimental equipment.

Demetriades-Tsafka-Kokkalis Prize in Biotechnology or Related Fields
Awarded annually to a Ph.D. candidate for the best thesis, publication, or discovery in biotechnology or related fields at the Institute in the preceding twelve months. Winners are selected by the bioengineering faculty. This award has been made possible by a gift from Anna Kokkalis Demetriades and Sterge T. Demetriades, Eng. '58.

Demetriades-Tsafka-Kokkalis Prize in Entrepreneurship or Related Fields
Awarded annually for the best business plan or proposal, start-up, thesis, publication, discovery, or related efforts by student(s) in entrepreneurship or related fields at the Institute in the preceding twelve months. This 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 twelve 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 by student(s) in benign renewable energy sources or related fields at the Institute in the preceding twelve months. 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.

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, up to $5,000, 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 Dean's Award for Outstanding Community Service
This award is made annually to a Ph.D. candidate who, throughout his or her graduate years at the Institute, has made great contributions to graduate life and whose qualities of leadership and responsibility have been outstanding.

Scott Russell Johnson Prize for Excellence in Graduate Study in Mathematics
Four prizes of $5,000 will be given to continuing graduate students for excellence in one or more of the following: extraordinary progress in research, excellence in teaching, or excellent performance as a first-year graduate student. The executive officer for mathematics, in consultation with the faculty, determines the recipients. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. ’83.

Scott Russell Johnson Graduate Dissertation Prize in Mathematics
A prize of $2,000 is awarded for the best graduate dissertation in mathematics. The prize may be split between two students. The executive officer for mathematics, in consultation with the faculty, selects the recipient. The prize is made possible by a gift from Steve and Rosemary Johnson in memory of Scott Johnson, B.S. ’83.

The Herbert Newby McCoy Award
A cash award is made annually to a graduate student in chemistry to acknowledge an “outstanding contribution to the science of chemistry.” The awardee is chosen by a faculty committee, based on solicited nominating packages, and the award-winning research is presented in a formal divisional seminar given by the awardee.

The McCoy award was established in 1965 as a result of a bequest of Mrs. Ethel Terry McCoy to honor her husband, who did pioneering work in the chemistry of rare earths and was associated with Caltech through collaboration with chemists Linus Pauling and Howard Lucas.

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 of $1,000 is made annually to an aeronautics student who has made the most significant contribution to the teaching and research efforts of the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT), with preference given to students working in structural mechanics.

The Ernest E. Sechler Memorial Award in Aeronautics was established in 1980 in memory of Ernest E. Sechler, who was one of the first graduates of GALCIT and who then served as a GALCIT faculty member for 46 years. Throughout his career Sechler was the faculty adviser for aeronautics students. In addition, he made many contributions to structural mechanics in areas ranging from aeronautics to the utilization of energy resources.

John Stager Stemple Memorial Prize in Physics
A prize of $500 is awarded annually to a graduate student in physics for outstanding progress in research as demonstrated by an excellent performance on the oral Ph.D. candidacy exam. John S. Stemple was a Caltech physics graduate student when he died; a memorial fund was established from contributions made by the community of Falls Church, Virginia, John's hometown.

Charles Wilts Prize
Awarded for outstanding independent research in electrical engineering leading to a Ph.D.

Note: Prizes and awards may be subject to federal and state income tax.

SPECIAL REGULATIONS OF GRADUATE OPTIONS

Aerospace

Aims and Scope of the Graduate Program
The Institute offers graduate programs in aerospace leading to the degrees of Master of Science in Aeronautics or Space Engineering, Aerospace Engineer, and Doctor of Philosophy. 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 asked to submit Graduate Record Examination scores with their applications.

In working for 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 and materials.

While research and course work in the aerospace option at the Institute cover a very broad range of subjects, a choice of one of the above fields allows students to focus their activities while taking advantage of the flexibility offered by the breadth of interests of the Graduate Aerospace Laboratories (GALCIT). A student with an interest in energy-related subjects will find many suitable courses and research projects of particular use. Subjects of major importance in the efficient use of energy, such as turbulent mixing, drag reduction, and flexible lightweight structures, have historically been the focus of research activity in the aerospace option.

In consultation with his or her adviser, a student may design a program of study in one of the above fields, consisting of the fundamental courses prescribed in the regulations for the separate degrees listed below, and of electives selected from the list of aerospace-related courses. Special attention is called to the list of courses numbered Ae 200 or higher.

Examinations, Committees, and Student Responsibilities

To help the student achieve satisfactory progress in his or her academic pursuits, the aerospace faculty provides for the following committee and individual support.

Upon entering aerospace for the master's program, each student is assigned a faculty (course) adviser whose research field matches the interests of the student as described in the latter's statement of purpose in his or her admissions application. This adviser, besides supervising the student's academic performance during that program, may also serve as a personal counselor. During the master's year, the GALCIT director and the option representative, as well as the elected student representative, are also available for counseling (see below).

In order to pursue studies beyond the master's degree and toward the degree of Aerospace Engineer, a student has to select and be accepted by a research adviser. The research adviser may be the former course adviser or a different faculty member. The research adviser and the student select a three-person committee. It is the responsibility of the student to initiate this selection process before the beginning of the post-master's studies. It is also the student's responsibility to have this committee meet three times during the last year of his or her residency before receiving the degree of Aerospace Engineer.

Students wishing to pursue studies leading to the Ph.D. are required to pass a qualifying examination in the first term of the year following completion of their M.S. studies, or, for students entering with an M.S., during the second year of their residency. Having passed the qualifying examination, the student's work continues to be guided by the three-person committee until he or she is ready to enter candidacy for the Ph.D. The four-member Candidacy Examination Committee shall include the student's research adviser. The Candidacy Committee is chaired by a faculty member other than the research adviser.

Conferral of the Ph.D. degree is contingent on satisfactorily passing the thesis examination before a four-person committee, which may, but does not need to, have the same constitution as the Candidacy Committee.

Problem and Grievance Resolution within Aerospace
Students may pursue several avenues for redress concerning personal and academic problems that may arise during their residency. Any member of the supervising committee at the time (three-person or candidacy committee) is accessible for relevant discussion, as are the director and option representative. In addition, two ombudspersons are available, one at the student and one at the faculty level. The student representative is elected annually by the aerospace graduate students at or after the Information Session, which is part of Ae 150 a. 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 (at present, an emeritus faculty member), chosen by the aerospace faculty, acts as an ombuds-person available for student contact. The names of the current student and faculty ombudspersons are available in the aerospace office.

Master's Degree in Aeronautics and Master's Degree in Space Engineering
Admission. Students with a baccalaureate degree equivalent to that given by the Institute are eligible to seek admission to work toward the master's degree in aeronautics or toward the master's degree in space engineering. Applicants are encouraged to indicate their desire to continue studies past the master's degree.
Course Requirements. A program of study consists of courses totaling at least 138 units; of these, at least 84 units must be in the following subject areas:

Fluid mechanics	27 units
Solid/structural mechanics	27 units
Mathematics or applied mathematics	27 units
Aerospace engineering seminar	3 units

An additional 27 units are required as follows: a course in experimental techniques and laboratory work for the master's degree in aeronautics, and a course in space engineering for the master's degree in space engineering. For the space engineering degree, the remaining 27 units of electives are to be chosen from courses at Caltech that support the broader goals of the space engineering program, subject to the approval of the option representative. Students must have a proposed program approved by their adviser prior to registration for the first term of work toward the degree.

Admission to More Advanced Degrees
Students wishing to pursue the more advanced degrees of Aerospace Engineer or Ph.D. must file a petition to continue work toward the desired degree. Students registering for the engineer's degree may transfer to study for the Ph.D. upon satisfactory completion of the same qualifying examination required of those work-

ing for the Ph.D. However, once admitted to work for the Ph.D. degree, students are not normally permitted to register for work leading to the engineer's degree. All students working for the engineer's degree or the Ph.D. degree are expected to register for and attend one of the advanced seminars (Ae 208 abc or Ae/AM 209 abc).

Degree of Aerospace Engineer

The degree of Aerospace Engineer is considered to be a terminal degree for the student who desires advanced training more highly specialized than the master's degree permits, and with less emphasis on research than is appropriate for the Ph.D. degree.

Admission. Students with a Master of Science degree equivalent to that given by the Institute may seek admission to work for the engineer's degree.

Program Requirements. The degree of Aerospace Engineer is awarded after satisfactory completion of at least 138 units of graduate work equivalent to the Master of Science program described above, plus at least 135 additional units of advanced graduate work. This latter program of study and research must consist of

- not less than 60 units of research in aerospace (Ae 200);
- three units of an advanced seminar such as Ae 208; and
- satisfactory completion (with a grade of C or better, or Pass) of at least 27 units of aerospace courses numbered Ae 200 or higher, or CE/Ae/AM 108, Ae/ME 120, and Ae/Ge/ME 160, excluding research and seminars.

A proposed program conforming to the above regulations must be approved by the student's adviser prior to registration for the first term of work toward the degree.

A thesis is required based on the research program and may consist of the results of a theoretical and/or experimental investigation or may be a comprehensive literature survey combined with a critical analysis of the state of the art in a particular field.

No student will be allowed to continue to work toward the degree of Aerospace Engineer for more than six terms of graduate residence beyond the baccalaureate degree (not counting summer registrations) except by permission after petition to the aerospace faculty.

Degree of Doctor of Philosophy

Admission. Students with a Master of Science degree equivalent to that given by the Institute may seek admission to work for the Ph.D. degree. In special cases, students may be admitted to Ph.D. work without first obtaining the master's degree.

Qualifying Examination. Because of the broad spectrum in the backgrounds of graduate students entering the Ph.D. program in aerospace, the student must first pass a qualifying examination to determine whether he or she is qualified to pursue problems typical of Ph.D. work. Emphasis in the qualifying examination is directed at determining if the student is properly prepared and qualified to undertake graduate research. The exams will cover the following subjects:

a. Fluid Mechanics (Ae/APh/CE/ME 101 abc)
b. Solid Mechanics (Ae/AM/CE/ME 102 abc)
c. Mathematics (ACM 100 abc)

The material covered in these examinations is at the same general level and breadth as covered in the corresponding M.S.-level courses. The examinations are offered during one week in the first half of the first term, in the second year of graduate residence at the Institute.

A student is examined orally on all three of these topics. In the event of an unsatisfactory performance, the examining faculty members may permit a repeat examination in the appropriate topics. The repeat examination must be scheduled prior to finals week of the second term and must be completed before the end of the third term of the same year.

Candidacy. To be recommended for candidacy for the Ph.D. in aerospace, the applicant must have satisfactorily completed at least 138 units of graduate work equivalent to the above Master of Science program and must pass, with a grade of C or better, 27 units of graduate-level ACM courses beyond ACM 95/100, and 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 120 and Ae/Ge/ME 160, excluding research and seminars. If any of the above subjects were taken elsewhere than at the Institute, the student may be required to pass special examinations indicating an equivalent knowledge of the subject.

In addition to fulfilling these course requirements, the applicant must pass a candidacy examination in the second or third year of residence at the Institute. 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 problems in advanced research.

Minor. No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

Foreign Languages. The student is encouraged to discuss with his or her adviser the desirability of studying foreign languages.

Thesis and Final Examination. Before graduation, each candidate is required to give a public seminar presenting the results of his or her thesis research. For final examination and thesis completion, see also the general degree requirements and the section on Examinations, Committees, and Student Responsibilities regarding aerospace starting on page 265.

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.

Applied and Computational Mathematics

Aims and Scope of the Graduate Program

The Institute offers an interdisciplinary program of graduate study in applied and computational mathematics leading to the Ph.D. degree. This program is designed to give students a thorough training in fundamental computational and applied mathematics and to develop their research ability in a specific application field. The fields of application include a wide range of areas such as fluid mechanics, materials science, and mathematical biology, engineering applications, image processing, and mathematical finance. The training essential for future careers in applied mathematics in academia, national laboratories, or in industry is provided by completion of the requirements for a Ph.D. degree in applied and computational mathematics.

The research areas and interests of the applied and computational mathematics faculty cover a broad spectrum, including nonlinear dynamics, computational biology, numerical analysis and scientific computing, computational and theoretical fluid mechanics, theoretical materials science, multiscale computations and homogenization theory, computational methods for electromagnetics and acoustics, statistics, signal and image processing, probability theory and stochastic analysis, and dynamical systems and geometric mechanics. As reflected by the faculty research activities, there is a strong emphasis on computational methods for solving challenging problems arising from engineering and scientific applications.

Reflecting the interdisciplinary nature of the program, several different groups, in addition to the applied and computational mathematics faculty, contribute to the teaching and supervision of research. Students in applied and computational mathematics are expected to combine their basic mathematical studies with deep involvement in some field of application. Basic general courses are listed specifically under applied and computational mathematics and these are to be supplemented, according to the student's interest, from the whole range of Institute courses in specific areas of physics, biology, engineering, etc.

A regular colloquium provides the opportunity for visitors, faculty, and students to discuss current research.

Admission

Each new graduate student admitted to work for the Ph.D. in applied and computational mathematics is given an informal interview on Thursday or Friday of the week preceding the beginning of instruction for the fall term. The purpose of this interview is to ascertain the preparation of the student and assist him or her in mapping out a course of study. The work of the student during the first year will usually include some independent reading and/or research.

Course Requirements
All ACM students are required to take a total of 18 nine-unit courses at the graduate level (or the equivalent of 162 units) during their graduate study at Caltech. Among these 18 courses, the following core courses, typically taken during the student's first year of study, are required: ACM 101 abc, ACM 104, ACM 105, ACM 106 abc, ACM 116, and an application elective course. The application elective course in the first year is selected, with the recommendation of the student's adviser, from among a wide range of courses offered by an outside option within the Institute. In the second and third years, students are expected to take graduate-level courses appropriate to their chosen research area. The remaining 81 units would normally include graduate-level ACM or CDS courses such as ACM 113, 201 abc, 210 abc, 216, 217, CDS 140 ab, 202, etc., as deemed appropriate to the student's research program, and which must be selected in consultation with the student's research adviser.

Students who have already taken some of the required courses may use them to satisfy the course requirements, even though the units may not be used to satisfy the total unit requirement for the Ph.D. degree. In addition, the student is required to enroll in ACM 290 for each quarter that he or she is in residence.

Master's Degree
Entering graduate students are normally admitted for the Ph.D. program. The master's degree may be awarded in exceptional cases. Of the 135 units of graduate work required by Institute regulations, at least 81 units of advanced graduate work should be in applied mathematics.

Degree of Doctor of Philosophy

The Candidacy Examination. In order to be recommended for candidacy the student must, in addition to satisfying the general Institute requirements, pass an oral or written candidacy examination administered by a faculty committee. This examination is offered during one week at the end of the first year of graduate residence at the Institute, typically near the beginning of the fall term. The material covered in this examination is based on the three core sequences described above. For students who have already taken the required courses before coming to Caltech, the examination can also be based on the substituted courses taken in the first year.

Advising and Thesis Supervision. Upon passing the candidacy examination (usually by the end of the second year), the student is required to choose a thesis supervisor who assumes the major responsibility in supervising the Ph.D. thesis. At the same time, an advising committee consisting of three faculty members is formed to help oversee the advising process. This committee should be formed no later than the third year of graduate study. The student's supervisor is part of this committee, but does not chair the committee. The student is encouraged to meet with the committee members informally for advice or suggestions. Joint supervision between two faculty members is also possible as is seeking a thesis adviser outside the core applied and computational mathematics option, although in this case it is mandatory that an applied mathematics faculty member be nominated as a co-adviser.

Should a disagreement of any kind occur between the student and his or her supervisor as regards the timely completion of the thesis, the student is encouraged to direct his or her concerns to the committee chair. If this is not workable, the student should feel free to consult with the option representative, the executive officer, or an applied and computational mathematics faculty member of the student's choice. If the student's concerns cannot be resolved through consultation with these individuals, the student is encouraged to pursue resolution of his or her concerns through other channels as outlined in Student Grievance Procedure on page 49.

Submission of Thesis. On or before the first Monday in April of the year in which the degree is to be conferred, a candidate for the degree of Ph.D. in applied and computational mathematics must deliver a typewritten or printed copy of the completed thesis to his or her research supervisor.

Final Examination. The final oral examination is held within four weeks after the submission of the thesis. The examination covers the thesis and related areas.

Subject Minor in Applied and Computational Mathematics

The group of courses must differ markedly from the major subject of study and must include 54 units of advanced courses in applied mathematics. The qualifying courses exclude the basic courses listed under ACM, from ACM 100 to ACM 106, although some flexibility is allowed depending upon the department 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.

Subject Minor in Applied Computation

The subject minor in applied computation is administered jointly by the applied mathematics and computer science options, and is open to graduate students in all options. This minor emphasizes the mathematical, numerical, algorithmic, and programming methods underlying the application of computation—particularly parallel and concurrent computation—to research in science and engineering.

To pursue the applied computation minor, applied mathematics students should seek a minor adviser in computer science; computer science students should seek a minor adviser in applied mathematics; and students in other options should seek a minor adviser in either applied mathematics or computer science. The minor adviser and the student formulate a program of courses individually tailored to the student's background and needs, with the objective that the student achieve a level of competence in specific subjects relevant to applied computation that is comparable to that of candidacy-level graduate students in applied mathematics *and* computer science in these same subjects. These subjects include *at minimum* mathematical and numerical methods, algorithms, and advanced programming, and may also include other areas of particular relevance to a student's research area, such as specialized mathematical methods, computer graphics, simulation, or computer-aided design.

Each proposed program must be approved by a faculty committee composed of the option representatives of applied mathematics and computer science, and one faculty member appointed by the chair of each division from which students are enrolled in the program. The number of course units is variable, with a minimum of 45 units of graduate-level courses. The satisfaction of the intended level of competence is assured by the student's passing an oral examination.

Applied Mechanics

Master's Degree

Study for the degree of Master of Science in applied mechanics ordinarily will be completed in one academic year and must consist of courses numbered 100 or above totaling at least 138 units. The program must include ME 150 abc and one course from among the following: ACM 100 abc, AM 125 abc, or a substitute acceptable to the faculty in applied mechanics. Note that ACM 100 may not be used to fulfill the advanced mathematics requirement for the Ph.D. in applied mechanics. A minimum of 108 units of graduate-level courses must be selected from courses in AM, ACM, Ae, CE, and ME. The M.S. program must be approved by the student's adviser and the option representative for applied mechanics.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below concerning this degree.

Degree of Doctor of Philosophy

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 leading to a thesis is required.

Advising and Thesis Supervision. A counseling committee of three faculty members is appointed for each student upon his or her admission to work toward a Ph.D. degree in applied mechanics, in order to advise the student on a suitable course program. One committee member acts as committee chair and interim adviser until this responsibility is assumed by the thesis adviser. This committee must meet during the first and third terms of each year of Ph.D. study.

The thesis adviser and 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 or engineer.

Admission to or Continuation in Ph.D. Status. Newly admitted students, those continuing study toward the Ph.D. degree in applied mechanics, and all other graduate students wishing to become eligible for study toward this degree, must make satisfactory progress in their academic studies each year, as judged by a special joint faculty committee.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in applied mechanics, the student must, in addition to the general Institute requirements, meet the following:

- Complete 27 units of research.
- Complete at least 108 units of advanced courses arranged by the student in conference with his or her adviser and approved by the faculty in applied mechanics.
- Pass with a grade of at least C an additional 27 units of course work in advanced mathematics, such as AM 125 abc or a substitute acceptable to the faculty in applied mechanics.
- Pass a two-part oral candidacy examination in the second academic year of graduate residence at the Institute.

Thesis and Final Examination. A final oral examination will be given after the thesis has been formally completed. This thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

Subject Minor

A student majoring in another branch of engineering, or another division of the Institute, may elect applied mechanics as a subject minor, with the approval of the faculty in applied mechanics and the faculty in his or her major field. The group of courses shall differ markedly from the major subject of study or research, and shall consist of at least 54 units of courses approved by the faculty in applied mechanics. The student must pass an oral examination that is separate from the examination in the student's major.

Applied Physics

Aims and Scope of the Graduate Program

The faculty in applied physics anticipate that a professional in the field will be able to solve problems of a physical nature by using a combination of analysis, engineering tools, and technological innovation. Graduate study in applied physics at Caltech is therefore designed to cover considerable ground in sufficient depth to prepare the student broadly for any technical challenge that lies ahead. Completion of core preparatory classes during the first two years is normally followed by an additional three years of independent and original research culminating in the Ph.D. The goals of this program are to develop competence in a chosen field of specialization; to develop tools with which to assess problems outside one'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 applied physics is strictly a doctoral program; students seeking a terminal master's degree should not apply.

Degree of Doctor of Philosophy

In preparation for the candidacy exam, which must be taken prior to the start of the third year in residence, the student must obtain a minimum of 135 units from the following list of core courses: Ph 106; Ph/APh/Ch 125; ACM 101 or AM 125 or Ph 129; APh 105 or Ph 127; and one additional three-term sequence, which may include Ae/APh/CE/ME 101, APh 114, APh 115A, Ph 156, or BE/APh 161/162. All first-year graduate students are also required to attend the weekly seminar class, APh 110 ab, to learn about ongoing research projects with the applied physics option. Students wishing to substitute more advanced material for the courses listed above must obtain prior approval from the option representative. In preparation for candidacy, students are also strongly encouraged to sample more advanced courses in their subfield of interest including but not limited to APh 130, APh 131, APh 132, Ph 135, Ph 136, EE/APh 180, APh/EE 183, APh 190, and Ph/APh 223. The student's research adviser or the option representative can be consulted for additional recommendations. No more than 27 units of research in APh 200 may be counted toward this limit. Only courses in which the student has obtained a grade of C or higher can be counted toward this sum.

To be recommended for candidacy to the doctoral program, a student must satisfactorily complete the three requirements below:

- *Demonstrate competency in the following basic areas of physics and engineering* at the level indicated:
  1. Classical Physics: Mechanics and Electromagnetism (Ph 106)
  2. Quantum Mechanics (Ph/APh/Ch 125)
  3. Mathematical Methods (ACM 101 or AM 125 or Ph 129)
  4. Statistical Physics and Thermodynamics (APh 105 or Ph 127)
  5. Biophysics or Fluid Physics or Plasma Physics or Solid-State Physics (Ae/APh/CE/ME 101, APh 114, APh/Ph 115, APh 156 or BE/APh 161 and 162).

The student will also be expected to demonstrate proficiency for clear and precise self-expression both in oral and written English.

- *Oral examination*. This examination must be taken before the beginning of the student's third year in residence. 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 a more open-ended discussion to test general proficiency in various subfields of applied physics. 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 PhD. Upon recommendation of the examining committee, however, the student may be granted a terminal master's degree.
- *Research proposal.* The student must have selected a thesis adviser and have completed a minimum of 18 units of research activity under his/her direction by the end of the second year in residence. At the oral examination, the student will discuss the research topic of choice, describe progress to date, and present a research plan for further study. Students whose research component is deemed insufficient or unsatisfactory will be asked to retake the candidacy exam a second time.

Students who fulfill these three requirements will have successfully completed the candidacy exam and will receive a master's degree in applied physics.

Thesis and Final Examination. The candidate shall undergo a broad oral examination 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.

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 B- or higher 81 units of courses in applied physics above the 100 level, excluding APh 200. Students cannot use courses required by their major option in fulfillment of this requirement. Students interested in a minor must receive prior approval from the option representative in applied physics, who will review and approve the proposed course of study. It is recommended that this course of study include advanced courses spanning different subfields of applied physics.

Astrophysics

Aims and Scope of the Graduate Program

Modern astronomy—certainly as practiced at Caltech—is essentially astrophysics. With the goal of understanding the physical processes that govern the universe, its constituents, and their evolution, astronomy uses the apparatus and methodology of physics to gather and interpret data. In what follows, we use the terms astronomy and astrophysics interchangeably.

The primary aim of the graduate astrophysics program at Caltech is to prepare students for creative and productive careers in astrophysical research. 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.

Admission

Incoming students should have a strong background in physics, and although a good preparation in astronomy is helpful, this is not required for admission to the graduate program. All applicants, including those from foreign countries, are requested to submit Graduate Record Examination scores for verbal and quantitative aptitude tests and the advanced test in physics.

Placement Examination

Each student admitted to work for an advanced degree in astrophysics is required to take the placement examination in physics (see Placement Examinations, page 331) covering material equivalent to Ph 106, Ph 125, and Ph 129. This examination will test whether the student's background is sufficiently strong to permit advanced study in astrophysics. If it is not, students will be required to pass the appropriate courses.

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 department. At least 36 units of the 135 units must be selected from Ay 121–127. The courses Ph 106, Ph 125, and Ph 129 may be required of those students whose previous training in some of these subjects proves to be insufficient. At least 27 units of advanced courses in fields other than astronomy are required.

Degree of Doctor of Philosophy

Astrophysics Program. The student's proposed overall program of study must be approved by the department 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. Observational astronomy students should also take Ay 122. Also required are research and reading projects. Credit for this work will be given under courses Ay 142 and Ay 143.

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 by the option representative or executive officer. Cross-listed courses (e.g., Ph/Ay) in general do not count toward the physics units requirement, unless specifically allowed by prior consultation between the student, the instructor, and the student's option representative. This requirement may be reduced on written approval of the department for students who take substantial numbers of units in Ph 106, Ph 125, and Ph 129. Students in radio astronomy may substitute an advanced course in electrical engineering or applied mechanics for up to nine units of the required 36 units of physics. Theoretical astrophysics students should include at least 54 units of physics courses in their programs. Students in planetary physics may substitute appropriate advanced courses in geophysics and geochemistry. All the above courses must be passed with a grade of C or better, or a P upon prior written permission from the option representative to take the course pass/fail.

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, required of all students in their second year and all subsequent years.

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 with a grade of B or better, or by special examination, Ay 121, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127; and also Ay 122 for observational astronomy students;
- 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 (at least one term 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 candidacy examination. Students will be examined on the substance and status, 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 receive more than two C (or lower) grades in the Ay 120 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 second term 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. Under no circumstances will students be permitted to continue beyond the third year without successful completion of all candidacy requirements.

After the oral candidacy exam, the adviser and the student together have primary responsibility for the student's progress and career development. To ensure that these remain on course, both student and adviser must submit annual progress reports to the executive officer (or in the case of a conflict of interest, to the astrophysics option representative or the division chair). If at any stage the student, the adviser, or the executive officer feels that there are serious problems developing, they may consult in confidence with the astrophysics option representative, the executive officer, or the division chair. They may also request a meeting of the oral candidacy exam committee or seek the advice or help of other faculty members. Students may also seek confidential advice and help from the Counseling Center and the Ombuds Office.

Final Examination. A final draft of the thesis must be submitted at least six weeks before the commencement at which the degree is to be conferred. At least two weeks after submission of the thesis, the student will be examined orally on the scope of his or her thesis and its relation to current research in astrophysics. The examination will be conducted by a committee selected in the same way as the oral candidacy committee. The examination should occur before the end of the fifth year. Only in rare circumstances will permission be granted to continue in a sixth year. Such permission requires a written petition to the executive officer.

Typical timeline:

Year 1: Ay 121, Ay 123–127; at least three advanced physics courses; reading and independent study. Begin research.

Year 2: Early fall—general oral candidacy examination. Research projects; select thesis and adviser. Fulfill teaching requirement. Complete 36 units of physics (54 for theorists); 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.

Year 4: Annual report from student and adviser. Ay 141.

Year 5: Annual report from student and adviser. Ay 141. Complete Ph.D. thesis before end of year 5. Final oral examination.

Subject Minor

The program for a subject minor in astrophysics must be approved by the department before admission to candidacy. In addition to general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in astronomy.

Behavioral and Social Neuroscience

Aims and Scope of the Graduate Program

The application of neuroscientific methods to the social sciences is a new frontier at the intersection of the social and natural sciences. Caltech is one of the few places in the world with deep expertise in neuroscience, behavioral economics, and political science. We have built bridges with faculty members in other divisions who are leading researchers in neuroscience. For these reasons we are in a unique position to train Ph.D. students in this new interdisciplinary area.

Students in the behavioral and social neuroscience (BSN) program receive in-depth training both in neuroscience and rigorous social science methods, and thus will be in a position to make significant research contributions at the intersection of the two disciplines.

Master's Degree

Entering graduate students are admitted to the Ph.D. program, and will earn the M.S. degree after successful completion of 135 units of course work. The program does not admit students who plan to obtain an M.S. degree only, but a student who does not go on to achieve a Ph.D. may leave with a terminal master's degree.

Admissions

Admission to the Caltech Ph.D. program is highly competitive, and those who are admitted have excellent GRE scores, impressive academic records as undergraduates, and highly supportive letters of recommendation. Entering students are expected to have a strong background in mathematics, and to have completed courses in calculus at the levels of Ma 2, linear algebra, and mathematical statistics.

Course Program

The program is designed to enable students to earn their Ph.D. in five years, although it is sometimes possible to finish in four years. During their initial three years in the program, students are expected to acquire competence in the core areas of neuroscience, statistics and econometrics, and either economics or political institutions/political behavior. The fourth and fifth years focus on research and writing, culminating in a dissertation and the granting of a Ph.D.

The first-year curriculum consists of the following required course work: decision theory, game theory, and social choice (SS 201 abc), econometrics (SS 222 abc), behavioral and social neuroscience (Bi/Psy 102 ab), neurobiology (Bi/CNS 150), computational neuroscience (Bi/CNS/CS 187), plus lab rotations 1–3 (with the third lab rotation completed during the summer). Courses are primarily nine units each, so students must register for at least 36 units each quarter. In order to make satisfactory progress, students must complete each class with a grade of B or better. Students should meet with the director of graduate studies (DGS) at least once a quarter to discuss their program and the progress they are making, and to address any difficulties that they might be encountering.

The second-year curriculum consists of the following required coursework: completion of the course sequences in foundations of economics (SS 205 abc) or political institutions and political behavior (SS 202 abc), as well as the graduate writing seminar (SS 281). Following the 36 unit requirement per term, the remaining units each term will be achieved by taking SS 300. Students must receive an average grade of B or better for coursework or a pass for SS 300.

During each of the first and second quarters of the third year curriculum, students take 15 units of research in social science (SS 300), supervised by their primary adviser, and at least two other graduate social science courses. One of these courses must be modern topics in social science (SS 280). This course exposes students to influential works in areas of social science that are not typically covered in the first- and second-year courses. In the third quarter students must enroll in at least one advanced social science course along with 24 units of SS 300.

Beginning in their third year and in all subsequent years, all students should also enroll in the three-unit graduate student seminar (SS 282) every quarter. Every student must make a presentation in this class at least once a year. The SS 300, 280, and 282 courses are all taken on a pass-fail basis.

The fourth year is a yearlong thesis workshop, which means students need to register for 33 units of SS 300 and three units of the graduate student seminar SS 282, all on a pass-fail basis.

During their fifth and final year in the program, students focus on obtaining a job (or a postdoctoral position) and on completing and defending their dissertation. Early in the first term, students need to complete a job-market paper, practice presenting that paper at an optionwide seminar, and assemble and mail job applications.

Progress Review Leading to Candidacy

At the end of the third quarter of the first year, students are required to take written preliminary examinations in theoretical foundations of social science (SS 201 abc) and econometrics (SS 222 abc). Each part requires three to four hours to complete. The exams are written by the instructors of the first-year course sequences, but are graded by the entire social science faculty. The results given are honors, pass, and fail. Students must achieve at least a pass in both parts. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the second year.

By the end of the second year, students must also satisfactorily complete and pass the prelim corresponding to either microeconomics (SS 205 abc) or political science (SS 202 abc) depending on which sequence they select to take. Again, each part requires three to four hours to complete. The exams are written by the instructors of the second-year course sequences, but are graded by the entire social science faculty. The results given are honors, pass, and fail. Students must achieve at least a pass in both parts. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the third year.

Also, by the end of their second year students are required to submit a research paper (which may be coauthored) to the DGS after having it approved by their two-person committee. During the spring quarter of the second year students should enroll in SS 300, a seminar devoted to work on their second-year paper, and SS 281, which focuses on scholarly writing and presentation. The primary adviser and second committee member will monitor and evaluate the progress on the second-year paper. If the two faculty reviewers find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will decide whether or not the paper is satisfactory. If they decide it is not, they may also vote to terminate the student from the program.

Third-year students must write a research paper (which may be coauthored), submit it to the DGS, and present it to the faculty by the end of the third quarter. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience. Ideally the third-year paper leads directly into dissertation research, but it is not a requirement that this be the case.

After the 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 also satisfactorily completed all previous requirements. If this evaluation is favorable, the student is admitted to candidacy for the Ph.D. At this point students need to file candidacy papers with the dean of graduate studies. If this evaluation is unfavorable, the student may be terminated from the program.

Organization of the Thesis Committee

By February 1, second-year students should have decided upon the general area in which they intend to pursue research and should therefore select a primary adviser whose work is related to their research interests. The adviser must be a faculty member in behavioral and social neuroscience at Caltech. The primary adviser will serve as chair of their dissertation committee. It is possible to change advisers if a student's research interests change. A second committee member, who should be a faculty member in either BSN or in social science, should be chosen by June 1 of the second year.

By the end of the third year, all students, in consultation with their advisers, should select a third committee member. This choice should be based on the content of ongoing dissertation research. It is not necessary that the third member be responsible for the full breadth of research covered by the dissertation, and in many cases the third member is selected to provide specialized help, e.g., in econometrics. Committee members may be chosen from outside the social science faculty, but such choices must be approved by the DGS.

Also by April 1 of the fourth year, students are required to have finalized the membership of their thesis committee. The committee consists of four members, one of whom is assigned by the chair of the Division of the Humanities and Social Sciences. Two members of the committee must be members of the social science faculty, and the committee must include at least one member of the social science faculty who does not specialize in neuroscience.

Ph.D. Degree Requirements

Satisfactory progress during the fourth and fifth years toward completion of the Ph.D. consists of the following.

By October 15 of the fourth year, a dissertation prospectus must be developed that outlines the proposed dissertation and sets a tentative schedule indicating when the various components of the dissertation are expected to be completed. This prospectus must be approved by the adviser and the second and third committee members before it is filed with the DGS.

Also, by April 1 of the fourth year, all students are required to convene a thesis proposal seminar with their adviser and other committee members. In this seminar they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. Students and their committee should thus reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation. While the committee chair/adviser is primarily responsible for monitoring progress on the dissertation, students also need to consult regularly with the other members of their committee and keep them informed as to the progress they are making and any problems they are encountering. It is also expected that in the fall of their fifth year, students will present an optionwide seminar in order to prepare for the job market.

After the dissertation has been completed, students, in consultation with their adviser, must schedule the oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research with a coherent theme. Successful completion implies that the faculty has certified that the student is a trained, professionally knowledgeable, and potentially productive scholar in his or her chosen area of work.

Biochemistry and Molecular Biophysics

Aims and Scope of the Graduate Program
An integrated approach to graduate study in biochemistry and molecular biophysics has been organized primarily by the Division of Biology and the Division of Chemistry and Chemical Engineering. The curriculum is designed to provide a broad background in biochemistry and biophysics of macromolecules and molecular assemblies, in addition to an appropriate depth of knowledge in the field selected for the Ph.D. thesis research.

Admission
The option in biochemistry and molecular biophysics is open to students with undergraduate degrees in biochemistry, biology, chemistry, biophysics, physics, engineering, and related areas. All applicants for admission, including those from foreign countries, are required to submit the verbal, quantitative, and analytical scores for the Graduate Record Examination and are also strongly urged to submit the results of an advanced test in a scientific field. Applicants whose native language is not English are required to submit results of the TOEFL exam, and, after admission, are required to satisfy the English language requirements of the Institute.

Master's Degree
Students are not normally admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met. In general, the degree is not conferred until the end of the second year of residence.

Degree of Doctor of Philosophy
The Option Graduate Study Committee will counsel and oversee the student's progress upon admission to the graduate program. In the first year of graduate study, the course requirement consists of a sequence of three core courses covering the biochemistry and biophysics of macromolecules and molecular assemblies (BMB/Bi/Ch 170 abc). These courses will expose the student to contemporary issues in biochemistry and molecular biophysics, and to the tools and methods that are essential for research in this area. Research advisers are normally selected at the end of the first year. In consultation with their adviser, students are expected to take three additional advanced courses of nine or more units in the first and second years that are appropriate for their particular research interests.

Laboratory Rotations. In consultation with the Option Graduate Study Committee and individual professors, students will choose three laboratories in which to do short research projects during their first year of residence. These laboratory rotations are designed to provide the student with an introduction to different areas of biochemistry and molecular biophysics. It is possible to waive some or all of the rotations by petitioning the Option Graduate Study Committee.

Admission to Candidacy. By the end of the sixth term of residency, the student will take an oral examination to assess mastery of the field of biochemistry and to evaluate research progress. As part of this examination, each student will submit a written research report summarizing the progress in their research, and an original research proposition in a field outside the student's chosen field of research. A candidacy examination committee will be assembled by the Option Graduate Study Committee to administer the examination. When the student advances to candidacy upon successful completion of the exam, this committee will become the thesis advisory committee and will meet with the student once a year to evaluate research progress. This committee will also serve as the Ph.D. thesis examination committee.

Thesis and Final Examination. Thesis research will be carried out under the direction of one or more faculty members in the biochemistry and molecular biophysics option. The thesis defense will consist of a thesis seminar, followed by an examination by the Ph.D. thesis committee.

Bioengineering

Aims and Scope of the Graduate Program

The bioengineering graduate program trains doctoral candidates to unite engineering analysis and synthetic approaches to solve frontier problems in biological engineering from molecular to organismal length scales. Ph.D. candidates must satisfy coursework and qualifying exam requirements for one of three tracks:

1. the devices and imaging track, focusing on the design and fabrication of devices for manipulating, imaging, analyzing or regulating biological systems;
2. the mechanics track, focusing on elucidating the role of forces and flows in biological development, function and disease, and in exploiting this understanding to engineer biological and nonbiological mechanical systems based on these principles;
3. the synthetic and systems biology track, focusing on the fundamentals of biological circuit design at the molecular, cellular and multicellular levels, emphasizing both the physical and information-processing aspects of biological circuits.

The goal of the doctoral program is to prepare students to become leading scientists and engineers in academia and industry.

Master's Degree

Students are not admitted to work toward the M.S. degree. In special circumstances, the M.S. degree may be awarded, provided Institute requirements are met. In general, the degree is not conferred until after admission to candidacy for the Ph.D. degree.

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. Each candidate must satisfy the coursework requirements for one of the three tracks. These requirements are intended to build upon undergraduate training and to complement concurrent research activities. All students must maintain a course load of 36 units each term during the first year, and receive a grade of C or higher in each course. An incoming student with prior proficiency in any required course can instead take an elective (including research rotations) with the approval of the option representative. However, all students will be responsible for the required material during the qualifying exam.

Devices and imaging track (Year 1, only)
BE 262, Physical and Synthetic Biology Boot Camp: prior to first term
Math: Three terms selected from ACM 100 abc, AM 125 abc
Biology: BE 151, 152
Core: Two terms selected from EE 185, APh 109, EE/BE 166, Bi 227
Electives: Three terms selected from Bi 145 ab, Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, APh 109, Ae/APh/CE/ME 101 abc, Ae/AM/CE/ME 102 abc, AM/CE 151 abc, Ph 106 abc, Ph 127 abc, CDS 140 ab, CDS 110 ab, BE/Ae 243, BE/APh 161, BE/APh 162, ChE/BE 163, Ph/EE 118 ab, EE/BE 166, APh/BE 130, APh/BE 131, APh/BE 132, Bi 150, Bi 227, ChE 103 abc, EE 185, EE 187
Research: Optional research rotations BE 200

Mechanics track (Year 1)
BE 262, Physical and Synthetic Biology Boot Camp: Prior to first term
Math: ACM 100 abc
Biology: Two terms selected from Bi 145 ab, BE 151, BE 152
Core I: Three terms selected from Ae/APh/CE/ME 101 abc, ChE 103 abc, ChE 151 ab, ChE 174
Core II: Three terms selected from Ae/AM/CE/ME 102 abc, Ph 127 abc, ChE/Ch 164
Research: Optional research rotations BE 200

Mechanics track (Year 2)
Electives: Two terms selected from BE/APh 161, BE/APh 162, Ae/BE 242, BE/Ae 243, ChE 174

Synthetic and Systems Biology track (Year 1, only)
BE 262, Physical and Synthetic Biology Boot Camp: Prior to first term
Math: ACM 100 b and two terms selected from ACM 100 ac, ACM/EE 116, ACM/ESE 118, either CDS 110 a or ChE 105
Biology: Bi/Ch 110, Bi/Ch 111, Bi/BE 250 c
Core: BE/APh 161, ChE/BE 163, ChE/BE 169
Research: Research rotations in three labs BE 200

Research Rotations. One-term research rotations allow first-year bioengineering graduate students to sample relevant research activities in several labs before selecting a Ph.D. adviser. Research rotations are required in the synthetic and systems biology track and highly recommended in the other tracks. Rotations should be organized by each student in collaboration with individual faculty.

Adviser Selection. Students are expected to select a Ph.D. adviser by the end of the third term of the first academic year. Each student is individually responsible for finding an appropriate adviser. Advisers may be chosen from the list of BE faculty, or from any of the faculty in the Divisions of Engineering and Applied Science, Chemistry and Chemical Engineering, and Biology. Advisers in other divisions may be chosen in consultation with the BE option representative.

Qualifying Examination. An oral qualifying examination will be administered to all bioengineering graduate students during the summer term following the first year of coursework. Each student will be examined on three subjects reflecting the required coursework in the selected track:
devices and imaging track: math, biology, either devices or imaging;
mechanics track: math, biology, either solid, fluid, or statistical mechanics;
synthetic and systems biology track: math, biology, core sequence.

Admission to Candidacy. Before the end of the spring term of the second year of residency, each student must 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 committee must be composed of three faculty, plus the adviser(s), including a minimum of two bioengineering faculty. The candidacy report should be submitted to the committee members at least one week before the oral exam. The student who fails to satisfy the candidacy requirements by the end of the second year in graduate residence will not be allowed to register in subsequent terms except with special permission from the option representative.

Thesis Examination. A final oral examination will be given after the thesis has been formally completed. The exam will consist of a public research presentation followed by a private defense with an exam committee consisting of at least three professors in addition to the adviser(s). 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.

Biology

Aims and Scope of the Graduate Program

Graduate students in biology come with very diverse undergraduate preparation—majors in physics, chemistry, mathematics, or psychology, as well as in biology and its various branches. The aims of the graduate program are to provide, for each student, individual depth of experience and competence in a particular chosen major specialty; perception of the nature and logic of biology as a whole; sufficient strength in basic science to allow continued self-education after formal training has been completed and thus to keep in the forefront of changing fields; and the motivation to serve his or her field productively through a long career.

In accordance with these aims, the graduate study program in biology includes the following parts: (a) the major program, which is to provide the student with early and intense original research experience in a self-selected subject of biology, supplemented with advanced course work and independent study in this subject; and (b) a program of course work designed to provide well-rounded and integrated training in biology and the appropriate basic sciences, which is adjusted to special interests and needs. An individual program will be recommended to each student in a meeting with the student's advisory committee (see below). The Division of Biology does not encourage applications from students who have pursued undergraduate study in biology at the Institute, because the broader perspective to be gained from graduate study in a different setting is considered to be essential for the full development of each student's potential. Exceptions to this policy may be considered by the faculty of the division if there are circumstances that indicate that it would be in the best interests of a student to pursue graduate study at the Institute.

Admission

Applicants are expected to meet the following minimal requirements: mathematics through calculus, general physics, organic chemistry, physical chemistry (or the equivalent), and elementary biology. Students with deficient preparation in one or more of these categories may be admitted but required to remedy their deficiencies in the first years of graduate training, with no graduate credit being granted for such remedial study. This will usually involve taking courses in the categories in which the student has deficiencies. In certain instances, however, deficiencies may be corrected by examinations following independent or supervised study apart from formal courses. Furthermore, the program in biology is diverse, and in particular fields such as psychobiology and experimental psychology, or in interdisciplinary programs, other kinds of undergraduate preparation may be substituted for the general requirements listed above.

When feasible, visits to the campus for personal interviews will be arranged before a final decision for admission is made. Graduate Record Examinations (verbal, quantitative, and an advanced test in *any* science) are required of applicants for graduate admission intending to major in biology. Applicants are encouraged to take these examinations and request that the scores be transmitted to Caltech, in November or earlier, to ensure unhurried consideration of their applications.

Master's Degree

The biology division 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 Bi 250 ab and Bi 252.

Degree of Doctor of Philosophy

Major Subjects of Specialization. A student may pursue major work leading to the doctoral degree in any of the following subjects: genetics; cellular biology and biophysics; immunology; cellular and molecular neurobiology; integrative neurobiology; developmental biology; and molecular biology and biochemistry.

At graduation, a student may choose whether the degree is to be awarded in biology or in the selected major subject. As part of their Ph.D. program, students may complete a minor in another graduate option, in accordance with the regulations of that option. Students should consult with their advisory committee in planning such a program.

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 biology division. 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 July 1 of the first year except in extraordinary circumstances. This requirement can be waived by the option representative.

Formal Classes. During the first year of graduate studies, students are required to take a course on responsible conduct of research (Bi 252), as well as any two courses of a three-term series (Bi 250 abc) that covers the breadth of fields represented in biology at Caltech.

During each year that they are matriculated in the Ph.D. program, students are required to take Bi 251 abc (Biolunch). Students will be required to present their thesis research in Biolunch during their second and fourth years of study.

In addition to these fixed requirements, during their time at Caltech all students must take one additional 200-series or upper-division 100-series course offered by the biology division. 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 fifth 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 April. (Although it is anticipated that this exam will be completed by April of the second year, it can be delayed until August of the third year if the thesis adviser and student so choose.) The examining committee comprises four faculty members, at least three of whom should hold full or joint professorial appointments in the Division of Biology. 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.

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, they are 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 biology division, 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

a. Completion of the first-year course requirements during the first year.
b. Joining a laboratory in which a student will perform thesis research before the end of the first year in residence.
c. Passing the oral and written parts of the qualifying examination and completing admission to candidacy before the start of the third year.
d. Holding a thesis advisory committee meeting in each subsequent year of studies, and having the thesis committee verify that satisfactory progress is being made.
e. Serving as a teaching assistant for one quarter of each academic year spent in residence.
f. Completing Ph.D. studies by the end of the fifth year.

In the event that the student, option representative, and adviser are in agreement, it is possible to make exceptions to the above guidelines and remain in good standing. Extension of thesis work beyond the end of the fifth year requires that the student petition the dean of graduate studies for permission to register for the sixth year. Extensions beyond the sixth year will be allowed only in unusual circumstances. Once a student has passed admission to candidacy, the responsibility for assessing satisfactory progress lies largely with the student's thesis advisory committee. If a majority of the committee deems that a student is not making satisfactory progress, the student is at risk of being removed from the program at any time at the discretion of the option representative.

Examination Committee. Requirements for the Ph.D. thesis and examination are determined by the Ph.D. examination committee that is appointed by the dean of graduate studies for each degree candidate. This committee is usually the same as the thesis advisory committee, but this need not be the case. The composition of the committee must be approved by the option representative. The committee usually has five members. At least three must be professorial faculty who hold a full or joint appointment in the biology division, 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, 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. A third copy is required for the division library.

Caltech-UCLA Medical Scientist Training Program (MSTP)

A joint program between Caltech and the UCLA Medical School has been established for the granting of the 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. A maximum of two students per year will be accepted into the joint program. The M.D. degree would be from UCLA and the Ph.D. would be awarded by Caltech. Ph.D. studies involving collaborations between laboratories at both institutions could lead to a joint degree with both schools being cited.

The current directors of the UCLA MSTP are Dr. Steve Smale and Dr. Kelsey Martin, and Caltech Professor Paul H. Patterson is the associate director. For more information, see http://www.medsch.ucla.edu/mstp.

Caltech-USC M.D./Ph.D. Program
A joint program between Caltech and the USC (Keck) Medical School has been established for the granting of the M.D./Ph.D. degree. Students do their preclinical and clinical work at USC, and their Ph.D. work with any member of the Caltech faculty.

Admission to this joint program is made through the usual USC process, checking a box indicating interest in the Caltech option. A maximum of two students per year will be accepted into the joint program. The M.D. degree would be from USC and the Ph.D. would be awarded by Caltech.

The current Director of the USC M.D./Ph.D. program is Dr. Robert Chow, and Caltech Professor Paul H. Patterson is the Associate Director. For more information, see http://www.usc.edu/schools/medicine/education/degrees_programs/mdp/mdphd.html.

Subject Minor
A student majoring in another division of the Institute may, with the approval of the biology division, 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 biology division, with each course passed with a grade of C or better. Approval of each program must be obtained from the biology graduate option representative. A student majoring in another division who elects a subject minor in biology may, if desired, arrange to have the minor designated as biology, rather than with the name of the specific minor subject.

Chemical Engineering

Aims and Scope of the Graduate Program
The general objective of the graduate work in chemical engineering is to produce individuals who are exceptionally well trained to apply mathematics; the physical, chemical, and biological sciences; and engineering to the understanding of systems involving chemical reactions and transport phenomena and to the development of new processes and materials. The program also strives to develop in each student self-reliance, creativity, professional ethics, and an appreciation of the societal impact of chemical engineering and the importance of continuing intellectual growth.

Admission

It is expected that each applicant for graduate study in chemical engineering will have studied mathematics, physics, chemistry, biology, and chemical engineering to the extent that these subjects are covered in the required undergraduate courses at Caltech. In case the applicant's training is not equivalent, admission may be granted but the option may prescribe additional work in these subjects before recommending him or her as a candidate for a degree.

Master's Degree

Course Requirements. At least 135 units of course work must be completed in order to satisfy the Institute requirements. These units must include ChE 151 ab, ChE 152, ChE/Ch 165, 18 additional units of advanced courses in chemical engineering, 27 units of science or engineering electives, and 18 units of general electives. Finally, the M.S. requirements include at least 27 units of research, ChE 280, which represent two terms of research under the supervision of a chemical engineering faculty member or a two-term industrial research or development project performed with a member of the faculty in cooperation with professional staff at a local industrial laboratory. At least three weeks before the end of the final term of residence, a research report on the work performed under ChE 280 must be submitted to a designated member of the faculty, who will ask that it be read and approved by two members of the faculty. In addition, the fulfillment of the research report requirement must be signed off by a designated faculty member on the M.S. candidacy form and a final copy of the research report submitted to the Office of the Dean of Graduate Studies no later than two weeks before the degree is to be conferred. Doctoral students who have been admitted to candidacy can use their approved candidacy report to satisfy the research report requirement of the M.S. degree.

Degree of Doctor of Philosophy

The work leading to the Ph.D. degree prepares students for careers in universities and in the research laboratories of industry and government. Usually the first year of graduate work is principally devoted to course work in chemical engineering and related subjects. Time is also devoted during this period to the choice and initiation of a research project. During the second year the student is expected to spend at least half time on research, and to complete the course work and candidacy requirements.

Admission. Upon arrival at Caltech, each prospective Ph.D. student will meet in consultation with members of the faculty so that they may evaluate the level of the student's preparation with respect to that expected at the Ph.D. level in the areas of kinetics, thermodynamics, and transport phenomena. These consultations are held to help the student set up a course program for the first year of study. A written copy of the recommendations will be entered into each student's permanent file.

Research Adviser. During the first term, the faculty meets with the first-year grad students to propose topics for Ph.D. research. Following these meetings, the students are expected to meet individually with the various faculty members to discuss proposed research and generally obtain information for choosing a research adviser. At the end of the first term, each student is required to submit three faculty names, listed in order of preference. Every possible effort will be made to accommodate the student's first choice, subject to an opening in the desired research group, availability of necessary funding, etc. The final decision will be made by the chemical engineering faculty in consultation with the students.

Oral Qualifying Exam. Each student is required to take a subject qualifying examination at the beginning of the second quarter in residence, the purpose of which is to examine expertise in kinetics, thermodynamics, and transport phenomena. The intended level of the exam is approximately that of the corresponding undergraduate courses at Caltech. Students who fail one or more of the three subjects may be permitted, by approval of the chemical engineering faculty, to repeat the examination on the failed subject immediately after the spring term. The format and topics of the examination are distributed to the first-year students at the beginning of the fall quarter.

Course Requirements. Students are required to take ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and an additional course from a designated list. Each student is required to complete either a subject minor, or a general program of courses outside chemical engineering consisting of at least 54 units. The choice of the 54 units is subject to certain guidelines and restrictions included in the chemical engineering graduate studies guide. The general program of courses must be approved *in advance* by the option representative. It is intended that the courses chosen should constitute some integrated program of study rather than a randomly chosen collection of courses outside chemical engineering. Within these guidelines, the only course specifically excluded is research in another option. A grade of C or better is required in any course and a grade point average of at least 3.0 is expected. The requirements for a subject minor in any option are listed in this catalog.

Candidacy Report/Examination. Before the end of the spring quarter of the second year of residence, each student must submit a written progress report on his or her research for approval by a specially constituted candidacy committee consisting of faculty members familiar with his or her general area of research. An oral examination is subsequently held by this committee to evaluate the student's ability to carry out research at the Ph.D. level. A student who fails to satisfy the candidacy requirements by the end of the second year in graduate residence will not be allowed to register in a subsequent term except by special permission of the option and the dean of graduate studies.

Admission to Candidacy. To be admitted to candidacy, the student must have passed the qualifying and candidacy examinations, must have had the candidacy report approved, and must have submitted an approved list of courses already taken or to be taken.

Thesis Review Committee. After a student passes the second-year candidacy exam, a faculty committee known as the *thesis review committee* will be appointed to review periodically the student's progress. Usually, the thesis review committee will include members of the candidacy committee, and will be appointed by the option representative based upon the student's recommendations. This committee will meet with the student before fall registration each year, either as a group or individually, to review progress, suggest improvements in research, etc. 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 or her committee before the annual review meeting.

Final Examination and Thesis. See page 252 and the option graduate studies guide for regulations concerning final examinations and theses. A copy of the corrected thesis is to be submitted to the chemical engineering graduate secretary for the chemical engineering library.

The final examination will include the candidate's oral presentation and defense of his or her Ph.D. thesis.

Subject Minor

Graduate students electing a subject minor in chemical engineering must complete 54 units of graduate courses in chemical engineering that are approved by the chemical engineering faculty. The 54 units will consist of no more than 18 units from ChE 101, 103 abc, 105, and 110 ab, and at least 36 units from ChE 151 ab, ChE 152, ChE/Ch 164, ChE/Ch 165, and a list of chemical engineering courses provided by the option representative. A 3.0 GPA is required for the courses taken.

Graduate Studies Adviser, Option Representative, and Chemical Engineering Graduate Studies Committee. During graduate studies the students will interact with several members of the chemical engineering faculty. The most intensive interaction will be with the research adviser, who will advise on all aspects of Ph.D. research and coursework and will approve various formal requirements. Each student will be assigned a graduate mentor to provide additional perspective on the student's progress and on any problems that may arise. The student will also interact with the members of the thesis review committee, as discussed earlier. In addition, they will interact with the option representative and the graduate studies adviser. During the first year, the graduate studies adviser will advise the students about choice of research adviser, choice of courses, and Ph.D. qualifying exams. The option representative is responsible for GRA (graduate research assistantship) or GTA (graduate teaching assistantship) assignments, beyond the first year, and for approval of the Candidacy and Thesis Review Committees and other formal requirements for the M.S. and Ph.D. degrees. Students may contact either of these two faculty members regarding any questions or problems. In a case where the relationship between a student and his or her research adviser becomes strained and the student desires advice or help from other faculty, he or she should consult with the Chemical Engineering Grad Studies Committee, consisting of the option representative, the graduate studies adviser, and the option executive officer.

Additional Information. Additional information about graduate study requirements and procedures is provided in the chemical engineering graduate studies guide, distributed annually to first-year chemical engineering graduate students.

Chemistry

Aims and Scope of the Graduate Program

The 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.

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 staff. Students then talk in detail with each of several staff members whose fields attract them, eventually settle upon the outlines of a research problem that interests them, and begin research upon it early in the 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.

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 unless the course is offered with only the pass/fail option. A grade of B or better is required for credit. 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 the Chemistry Graduate Study Committee. Alternatively, a student may complete a subject minor in another option, the course requirements being set by that option.

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 40 units of chemical research and at least 30 units of advanced courses in science. The remaining electives may be satisfied by advanced work in any area of mathematics, science, engineering, or the humanities, or by chemical research. Two copies of a satisfactory thesis describing this research, including a one-page digest or summary of the main results obtained, must be submitted to the divisional graduate secretary at least 10 days before the degree is to be conferred. In addition, the fulfillment of the thesis requirement must be signed off by a designated faculty member on the M.S. candidacy form and a final copy of the thesis submitted to the Office of the Dean of Graduate Studies 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 approving the thesis, signed by the staff member directing the research and by the chair of the Chemistry Graduate Study Committee.

Degree of Doctor of Philosophy
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 three members of the chemistry faculty. The committee should be considered as a resource for the student for the remainder of his or her studies. At the candidacy examination a student is asked to demonstrate scientific and professional competence and promise by discussing a research report and propositions as described below.

The research report should describe progress and accomplishments to date and plans for future research. Two original research propositions, or brief scientific theses, must accompany the report, and at least one must be well removed from the student's field of research. These propositions should reflect his or her breadth of familiarity with the literature, originality, and ability to pose and analyze suitable scientific research problems. The research report and propositions must be in the hands of the examining committee one week before the examination.

The result of the candidacy examination may be either (a) pass, (b) fail, or (c) conditional. Conditional status is granted when the committee decides that deficiencies in a student's research report, propositions, or overall progress can be remedied in a specific and relatively brief period of time. In order to change conditional to pass status, the student must correct the indicated deficiencies or in some cases schedule a new examination the following term. He or she must be admitted to candidacy at least three terms before the final oral examination. A student cannot continue in graduate work in chemistry (nor can financial assistance be continued) past the end of the sixth term of residence without being admitted to candidacy, except by petitioning the division for special permission. This permission, to be requested by a petition submitted to the Graduate Study Committee stating a proposed timetable for correction of deficiencies, must be submitted before registration for each subsequent term (including the summer following the sixth term of residence) until admission to candidacy is achieved.

Language Requirement. There is no formal foreign language requirement for the Ph.D. in chemistry. However, the division believes strongly in the professional importance to chemists of a knowledge of foreign languages and encourages their study prior to graduate work or while in graduate school.

Thesis Research Progress. Before the thirteenth term of graduate residence (excluding summer terms), the student will be expected to demonstrate satisfactory progress in the course of thesis research. To this end an informal meeting with the Ph.D. thesis committee will be held, at which time the student will present an oral summary of research completed to date as well as an outline of future research plans. The thesis committee will generally consist of the original candidacy committee plus an additional member of the faculty. Following the presentation, an appropriate timetable for completion of the degree requirements will be discussed and agreed upon. If the student has not progressed sufficiently, completion of the Ph.D. may be considered inappropriate.

Length of Graduate Residence. Any graduate student who anticipates a need to register for a 16th academic term must request a meeting of his or her thesis committee and present a 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 chair of the Chemistry Graduate Study Committee, and, in cases where financial support is an issue, also 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.

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 must be held before the end of the fifth year of residence, and not less than 10 weeks in advance of the final doctoral examination. A copy of the propositions, along with suitable abstracts, must be submitted to the examining committee and to the division graduate secretary not less than two weeks before the propositions examination. These propositions must be acceptable to the committee before the final doctoral examination can be scheduled.

A copy of the thesis must be submitted to each member of the thesis committee not less than two weeks before the final doctoral examination. A copy of the thesis should also be submitted to the Graduate Office for proofreading three weeks prior to the final doctoral examination. One reproduced copy of the thesis, corrected after proofreading, is to be submitted to the division graduate secretary for the divisional library. Two final copies (one on Permalife paper) are to be submitted to the Graduate Office.

Subject Minor

Graduate students in other options taking chemistry as a subject minor will be assigned a faculty adviser in chemistry by the Chemistry Graduate Study Committee. In consultation with this adviser, the student will work out an integrated program of courses, including at least 45 units of formal course work at the 100 level or above. This program must be approved by the Chemistry

Graduate Study Committee, and a grade of C or better in each course in the approved program will be required.

Civil Engineering

Preparation for the Graduate Program
Students who have not specialized in civil engineering as undergraduates, as well as those who have, may be admitted for graduate study. As preparation for advanced study and research, a good four-year undergraduate program in mathematics and the sciences may be substituted for a four-year undergraduate engineering course, with the approval of the faculty. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty.

Master's Degree
For the M.S. degree a minimum of 138 units of academic credit for courses numbered 100 or above is required. The program must include three units of CE 130 abc and at least 81 units of graduate-level courses in CE and AM. Students who have not had ACM 100 abc or its equivalent will be required to include ACM 100 in their program. The M.S. program must be approved by the student's adviser and the option representative for civil engineering. Ordinarily, the degree program will be completed in one academic year.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below concerning this degree.

Degree of Civil Engineer
Greater specialization is provided by work for the engineer's degree than for the master's. The candidate for this degree is allowed wide latitude in selecting his or her program of study, and is encouraged to elect related course work of advanced nature in the basic sciences. The degree of Civil Engineer is considered to be a terminal degree for the student who desires advanced training more highly specialized and with less emphasis on research than is appropriate to the degree of Doctor of Philosophy. However, research leading to a thesis is required for both degrees. The student should refer to Institute requirements for the engineer's degree.

Degree of Doctor of Philosophy
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 leading to a thesis is required. Examples of areas of research are described in section two.

Advising and Thesis Supervision. A counseling committee of three faculty members is appointed for each student upon his or her admission to work toward a Ph.D. degree in civil engineering, in order to advise the student on a suitable course program. One committee member acts as committee chair and interim adviser until this responsibility is assumed by the thesis adviser. This committee must meet during the first and third terms of each year of Ph.D. study.

The thesis adviser and 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 or engineer.

Admission to or Continuation in Ph.D. Status. Newly admitted students, those continuing to study toward the Ph.D. degree in civil engineering, and other graduate students wishing to become eligible for study toward this degree, must make satisfactory progress in their academic studies each year, as judged by a special joint faculty committee.

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:

- Complete 27 units of research.
- Complete at least 108 units of advanced courses, arranged in conference with his or her adviser and approved by the faculty in civil engineering.
- Pass an additional 27 units of course work in advanced mathematics, such as AM 125abc or a substitute acceptable to the faculty in civil engineering.
- Pass a two-part oral candidacy examination in the second academic year of graduate residence at the Institute.

Thesis and Final Examination. A final oral examination will be given after the thesis has been formally completed. Copies of the completed thesis must be provided to the examining committee two weeks prior to the examination. This thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in his or her specialized field of research.

Subject Minor

A student majoring in another branch of engineering, or in another division of the Institute, may elect civil engineering as a subject minor, with the approval of the faculty in civil engineering and the faculty in the student's major field. The group of courses shall differ markedly from the major subject of study or research, and shall consist of at least 54 units of courses approved by the faculty in civil engineering.

Computation and Neural Systems

Aims and Scope of the Graduate Program

An integrated approach to graduate study combining computation and neural systems is organized jointly by the Division of Biology, 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, systems and cognitive neuroscience, computational biology and computational neuroscience, information and learning theory; emergent or collective systems; and computer science and electrical engineering; in conjunction with an appropriate depth of knowledge in the particular field of the thesis research. For more details, see http://www.cns.caltech.edu.

Admission

Applicants for admission to the option should have an undergraduate major in electrical engineering, biology, physics, chemistry, mathematics, or computer science and a strong interest that will permit enrolling in courses in all the relevant disciplines. All applicants for admission, including those from foreign countries, are strongly urged to submit Graduate Record Examination test scores for verbal and quantitative aptitude tests and for an advanced test in physics, biology, engineering, or mathematics.

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 their residency at Caltech as part of their Ph.D. graduation requirement.

Master's Program

Only students who expect to pursue the Ph.D. degree will be admitted to the option. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the option breadth requirements (see following section), the completion of a master's thesis, and receiving from a candidacy examination oral committee a recommendation for awarding the degree.

Laboratory Rotations
Mandatory rotations through research groups (labs) provide a unique opportunity for the student to experience the CNS culture. To broaden the student's knowledge and to provide familiarity with different techniques and ways of thinking or doing research, each student should carry out three 12-week laboratory rotations (one per term) during the first year, and should engage in research. During each rotation, the student is expected to take part in the life and routine of the lab by attending lab meetings; participating in research projects and discussions with members of the lab; and meeting monthly with the faculty of that lab to discuss science.

Course Requirements
Six nine-unit courses are required during the first year: CNS/Bi/Ph/CS 187, either Bi 9 or equivalent, or Bi/CNS 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/Psy 120, CNS/Bi/EE 186, CNS 187, Bi/CNS 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
Five 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. Advancing to candidacy requires passing 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, are available on the Web at http://www.cns.caltech.edu, providing a clear idea of the scope of knowledge that each student is expected to know well. Students are encouraged to organize working and discussion groups to prepare for this exam; the format and implementation of such a system, however, is left to the students.

This is an oral exam, with the five faculty (including the heads of the student's three rotation labs and two others chosen for "breadth," of whom one can be from outside Caltech). It should be scheduled by the student (who contacts the committee members) to take place during the last six weeks of the third term of year one. For the exam, the student must answer questions (from more than one category) taken from the list, which is modified each year. (The exam can be retaken after three months.)

The research and candidacy exam satisfies the depth requirement. During year two, the student is expected to produce a piece of work of a quality sufficient to be presented at a professional meeting. (The objective of this description is to offer a way to calibrate the level of expected research achievement and involvement. Professional acceptance of the abstract or paper is not a requirement for passing candidacy.) This work is presented in an oral exam in spring term of year two, before the same exam committee (if possible) that conducted part one of the exam. The exam focuses exclusively on research (accomplished and/or planned). During year two, the student may take other courses, as needed, but is expected to present a high standard (quality, originality) of research at the time of this second part of the candidacy exam.

Subject Minor: Students majoring in other fields may take a subject minor in CNS, provided the program is supervised by a CNS adviser, is approved by the CNS option representative, and consists of 45 units, including Bi/CNS 150, CNS/Bi/Ph/CS 187, Bi 252, and other CNS cross-listed classes. A subject minor is not required for the Ph.D. degree in CNS.

Computational Science and Engineering

Aims and Scope of the Minor

Computational Science and Engineering (CSE) may be pursued as a subject minor by graduate students who are pursuing Ph.D. degrees in any option. The CSE minor is intended to supplement one of Caltech's graduate degrees and is designed for students who wish to broaden their knowledge of CSE beyond their major field of study. The CSE minor is also intended to recognize graduate students' interest in and dedication to CSE as demonstrated by the successful completion of a program of study in the field. Completion of the CSE minor program of study will be recognized on the Ph.D. diploma by the statement, "…and by additional studies constituting a minor in Computational Science and Engineering."

Requirements

To receive the CSE minor, graduate students must fulfill the following requirements.

- 27 units (three terms) from the following list: ACM 106 abc, ACM 210 ab, ACM/CS 114, CS/EE/Ma 129 abc, CS 134, 136 abc, 138 abc, 139 abc, 150, 151, 175.
- 27 units (three terms) from the list: Ae/AM/CE/ME 214 abc, Ae/AM/ME 232 ab, Ay 199, Ch 121 ab, 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 on 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 will be administered by an oversight committee consisting of three faculty members reporting to the chair of the engineering and applied science division. In consultation with their advisers and, if needed, with the CSE Oversight Committee, students formulate a program of approved courses individually tailored to each student's background and needs, with the objective that the student achieve a level of competence in specific subjects relevant to CSE. Students must petition the CSE Oversight Committee for approval of their program of study. Upon completion of the program of study, the CSE Oversight Committee will verify that the CSE minor requirements have been fulfilled.

Computer Science

Aims and Scope of the Graduate Program
Graduate study in computer science is oriented principally toward Ph.D. research. The course work and thesis requirements for the M.S. degree are a required part of the Ph.D. program. There is no admission to the M.S. program as the degree objective.

Students entering the graduate program with an M.S. degree from another school may transfer credit for course work as appropriate. A student may petition the option representative to have a prior M.S. thesis or equivalent accepted in lieu of a Caltech M.S. thesis; no Caltech M.S. will be granted in this case.

The Ph.D. program requires a minimum of three academic years of residence. The M.S. should be completed within the first two years.

Students must maintain high academic standards during their graduate residence. A student's Ph.D. research must exhibit originality in the formulation, analysis, and solution of a problem that is significant to the field of study. The option representative and executive officers are available to discuss concerns regarding academic progress.

Master's Degree
There are five requirements to fulfill for the M.S. in computer science:

- *Total units.* Completion of a minimum of 135 units of courses numbered 100 or greater, including M.S. thesis research (CS 180). The student will consult with the adviser to ensure balance in the course work.

- *Advanced courses in computer science.* Completion of a minimum of 54 units of CS courses numbered 100 or greater in addition to units earned for reading, research, projects, and the M.S. thesis.
- *Units outside computer science.* Completion of a minimum of 27 units outside computer science. Courses jointly listed with computer science cannot be used to fulfill this requirement.
- *Breadth.* Toward the end of the first year, all incoming students must successfully pass a diagnostics exam administered by the faculty. Its purpose is to ensure a solid and broad knowledge in computer science, and/or to direct the students to necessary courses and reading.
- *M.S. thesis.* At the end of the second year, students must have completed a minimum of 45 units of CS 180, had their M.S. thesis approved by a computer science faculty member, obtained the signature of a designated computer science faculty member on the M.S. candidacy form, and submitted a copy of the M.S. thesis submitted to the Office of the Dean of Graduate Studies no later than two weeks before the degree is to be conferred.

Degree of Doctor of Philosophy

Candidacy. To be admitted to candidacy, a student must have completed the M.S. program, have entered upon a course of research approved by his or her thesis adviser, and have passed a candidacy oral examination. The candidacy oral examination will be administered by a committee that consists of four faculty, is approved by the option representative, and is chaired by the adviser. The examination will ascertain the student's breadth and depth of preparation for research in the chosen area. The examination should be taken within the first three years.

Advising and Thesis Supervision. In order to facilitate close supervision and a highly research-oriented environment, each student is admitted directly to an adviser and research group. A course of study is determined in consultation with the adviser. Occasionally students will be admitted into more than one group. Changes in affiliation may occur with the common consent of the student and the new adviser.

Students meet regularly with their adviser throughout their time at Caltech, and are encouraged to do the same with other members of the faculty.

Thesis and Final Examination. A final oral examination will be scheduled and given after the Ph.D. thesis has been submitted for review to the student's adviser and thesis committee; the latter consists of at least four faculty approved by the option representative, and is chaired by the adviser. The thesis examination is a defense of the thesis research and a test of the candidate's knowledge in his or her specialized fields.

Subject Minor in Computer Science

A subject minor is not required for the Ph.D. degree in computer science. However, students majoring in other fields may take a subject minor in computer science, provided the program is supervised by a computer science faculty adviser, is approved by the computer science option representative, and consists of 45 units sufficiently removed from the student's major program of study.

Subject Minor in Applied Computation

The subject minor in applied computation is administered jointly by the applied and computational mathematics and computer science options, and is open to graduate students in all options. This minor emphasizes the mathematical, numerical, algorithmic, and programming methods underlying the application of computation—particularly parallel and concurrent computation—to research in science and engineering.

The requirements are listed under Applied and Computational Mathematics.

Control and Dynamical Systems

Aims and Scope of the Graduate Program

The option in control and dynamical systems (CDS) is open to students with an undergraduate degree in engineering, mathematics, or science. The qualifications of each applicant will be considered individually, and, after being enrolled, the student will arrange his or her program in consultation with a member of the faculty. In some cases the student may be required to make up undergraduate deficiencies in engineering science courses.

The CDS option emphasizes the interdisciplinary nature of modern theory of dynamical systems and control. The curriculum is designed to promote a broad knowledge of mathematical and experimental techniques in dynamical systems theory and control. In addition to taking courses in the CDS option, students must select a focus area (see below).

Master's Degree

Students will be admitted to the option who expect to pursue the Ph.D. degree. The master's degree may be awarded in exceptional cases. The awarding of this degree requires fulfilling the Institute requirements for a master's degree, satisfying the focus requirements, and receiving a recommendation for awarding of the degree from the candidacy oral examination committee.

Degree of Doctor of Philosophy

Institute requirements for the Ph.D. degree are described in the section on degree requirements. Approximately two years of course work are required and two or more years are usually needed for preparation of the dissertation.

Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in control and dynamical systems, the student must, in addition to meeting the general Institute requirements, do the following:

- Complete the following courses: ACM/EE 116; CDS 140 a or Ma 147 ab; CDS 201 or Ma 108 ab; CDS 202 or Ma 109 ab.
- 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 science, fluid dynamics, information and communications, networking, robotics, and space systems. The program of study must be approved by the student's counseling committee and the option representative.
- Complete an additional 45 units in CDS or other advanced courses in systems theory, dynamical systems, and/or applied mathematics.
- Prepare a Research Progress Report.
- Pass an oral examination on the major subjects. The oral examination is normally taken before the end of the second year of graduate academic residence at the Institute.

Advising and Thesis Supervision. Upon admission each student is assigned an adviser in the option and a committee of three members, chaired by the adviser, which will approve the initial course of study by the student. A qualifying 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 the initial committee replaced by a (possibly identical) candidacy committee when the direction of specialization is determined, not later than the beginning of the second year. The candidacy exam is normally taken toward the end of the second year. The candidacy committee will be the judge of the completion of the engineering focus requirement, necessary before advancement to candidacy. The student's candidacy committee may be reconstituted as the thesis committee after the candidacy exam has been successfully completed.

At the early stages of thesis preparation, the student's thesis committee will meet as needed, but at least yearly, to advise the student of his or her progress and to deal with any problems that might have arisen.

A final oral examination will be given after the thesis has been formally completed. The thesis examination will be a defense of the doctoral thesis and a test of the candidate's knowledge in the specialized field of research. Normally this defense will consist of a one-hour public lecture followed by an examination of the thesis by the thesis committee.

Subject Minor
A student majoring in another option at the Institute may elect a subject minor in control and dynamical systems. He or she must obtain approval from the CDS faculty of a course of study containing at least 54 units of advanced courses with a CDS listing.

Electrical Engineering

Aims and Scope of the Graduate Program
Award of the Bachelor of Science degree may be followed by graduate study leading to the Master of Science degree in electrical engineering, and the more advanced degrees of Electrical Engineer or Doctor of Philosophy. Because admission to graduate studies in electrical engineering at Caltech is extremely competitive, the Admissions Committee attempts to select those applicants it judges both best qualified and best suited for the graduate program. Applicants should submit Graduate Record Examination scores.

Master's Degree
Normally, the master's degree in electrical engineering is completed in one academic year. The principal criteria for evaluating applicants for the MSEE are the excellence of their preparation for the math- and physics-oriented nature of Caltech's graduate courses, and the judgment of the Admissions Committee on their ability to successfully pursue and benefit from the course program. The Institute does not normally admit an applicant to the master's degree in a field in which the applicant already has a master's degree from another U.S. institution. Financial aid is seldom offered to those who intend to complete their graduate work with a master's degree. A joint B.S./M.S. degree is not available in electrical engineering.

135 units (100 or above except some specially petitioned humanities courses) are required as approved by the electrical engineering graduate student adviser. No more than 30 units of pass/fail grades may be counted toward this requirement. Units toward this are not transferable from other schools. At least 54 units of EE letter-
graded courses (courses listed or cross-listed as EE) labeled 100 or above and not counting EE 191 or EE 291 are required. EE 105 abc, Electrical Engineering Seminar, is also required. Students are urged to consider including a humanities course in the remaining free electives.

Students who have been admitted to the M.S.-only program must reapply if they are interested in the Ph.D. program.

Degree of Electrical Engineer
To be recommended for the degree of Electrical Engineer the applicant must pass the same subject requirements as listed for the doctor's degree.

Degree of Doctor of Philosophy

As a rule, applicants who wish to undertake research work leading to a degree of Doctor of Philosophy in electrical engineering are admitted initially only for the MSEE. They are, however, evaluated according to additional criteria, the most important of which is the applicant's interest in and potential for research in one of the areas described below. The statement of purpose required as part of the application should clearly address this match. Considerable weight is also given to the opinions expressed in the applicant's letters of recommendation.

During the Ph.D. applicant's master's degree year, evaluation continues. It is based in part on performance in courses and in part on a one-hour oral presentation scheduled early in the second quarter. As the year progresses, the electrical engineering faculty get to know the student, and the student makes contact with the professor in his or her area of research interest. Upon acceptance into a research group, the student begins research work and defers receiving the master's degree until formal admission into the Ph.D. program. Before the end of his or her second academic year of graduate study, the student normally takes the Ph.D. qualifying oral examination. This must, however, be done no later than the end of the third academic year.

Ph.D. applicants who already hold a master's degree in electrical engineering from another U.S. institution may be admitted directly to the Ph.D. program, but must provide sufficient information to obtain advance acceptance into a research group.

Financial aid available to a Ph.D. applicant includes teaching assistantships and fellowships. TA duties consist of grading papers or lab instruction but not classroom lecturing. A fellowship may be supplemented by a teaching assistantship, and either or both include a full tuition scholarship. Tuition scholarships alone are not available. If financial aid is not requested, or if the box on the application form labeled "willing to come without aid" is checked, information on the source of funds for each year of intended graduate study must be included.

Candidacy. To be recommended for candidacy for the doctor's degree, the applicant must satisfy the following requirements (and pass the Ph.D. qualifying oral examination) no later than the end of the third academic year:

- Complete 18 units of research in his or her field of interest.
- Obtain approval of a course of study consisting of at least 135 units of advanced courses in electrical engineering or the related subjects listed under the master's degree. Only up to 27 units in research (e.g., EE 291) may be counted in this total. No more than 30 units of pass/fail grades may be counted toward this requirement. The courses taken to satisfy the math requirement below and courses taken to fulfill the Master of Science degree requirement may be included

to satisfy this requirement. Units toward this requirement are not transferable from other schools.

- Pass 27 units of mathematics courses, as approved by the student's research adviser, with letter grade no lower than C.
- Pass a qualifying oral examination covering broadly the major field. Students are strongly encouraged to do this before the end of the second year of residency.

Ph.D. Committee. The Ph.D. qualifying oral exam and the final defense exam are conducted by committees that are set up by the student and approved by the option representative. Members of these Ph.D. committees also serve as second or backup mentors in cases where such additional advising and problem solving are appropriate.

Thesis and Final Examination. The candidate is required to take a final oral examination covering the doctoral thesis and its significance in and its relation to his or her major field. This final examination will be given not less than two weeks after the doctoral thesis has been presented in final form, and before its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted.

Advising and Thesis Supervision. Periodic meetings between the advising faculty and the graduate student are an integral part of the Ph.D. program. These meetings should be at sufficiently frequent intervals, as determined by the student and adviser. Students are also encouraged to meet with other members of the Ph.D. committee, the option representative, the executive officer, or Caltech's ombudsperson to discuss problems relating to satisfactory progress.

Subject Minor

A student majoring in another option at the Institute may elect a subject minor in electrical engineering. He or she must obtain approval from the electrical engineering faculty of a course of study containing at least 45 units (over the 100 level) of advanced courses with an EE listing (excluding EE 191 and 291). At least 36 of these should be for letter grades no lower than C. Freshman classes cannot be counted toward this.

Environmental Science and Engineering

Aims and Scope of the Graduate Program

The interdisciplinary problems posed by natural and human-induced changes in the earth's environment are among the most interesting, difficult, and important facing today's scientists and engineers. The environmental science and engineering option is an interdivisional program of study by biologists, chemists, earth scientists, engineers, and physicists to investigate the functioning of and interactions among the atmosphere, hydrosphere, biosphere, and lithosphere. The ESE option is administered by the Divisions of Chemistry and Chemical Engineering, Engineering and Applied

Science, and Geological and Planetary Sciences and promotes both broad knowledge of natural and engineered environmental systems and a detailed understanding of the application of basic science to environmental issues.

Admission
Applicants for admission to the option should have undergraduate preparation in science, engineering, or mathematics. Admission is limited to students intending to pursue the Ph.D. degree. Applicants are required to submit Graduate Record Examination (GRE) scores for the aptitude tests. Applicants from non-English-speaking nations are required to submit Test of English As a Foreign Language (TOEFL) scores.

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 and satisfy the ESE core requirement.

Advising
An academic adviser is appointed for each incoming student to assist in design of his or her academic program. The research adviser will be chosen by mutual agreement of the student and adviser before the end of the student's third term of graduate study. The thesis advisory committee (TAC), consisting of four faculty including the research adviser, will be constituted and will meet with the student soon after the student successfully completes the Ph.D. qualifying examination, and should thereafter meet with the student at least yearly. Committee membership may change with the student's research interests. TAC members will generally serve to approve the student's advancement to candidacy and as the examining committee for the final thesis defense.

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. The program of courses for the Ph.D. degree should be designed to educate students in the application of the basic sciences to environmental problems and to prepare them for their research. 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 Ph.D. program must include three units of ESE 150 abc and three units of ESE 101. Courses in mathematical physics, such as Ge 108, and in applied statistics and data analysis, such as ACM/ESE 118, are required for students lacking this preparation. Note that advanced courses in biology with a strong quantitative component may be substituted in appropriate cases upon petition by the student. Students are further required to take 18 units in each of the three core areas—environmental chemistry, biology, and physics—for a total of 54 units in the core courses. Courses satisfying the core requirements are

- *Environmental Biology:* ESE/Ge 148 c, ESE/Bi 166, Ge/ESE 170
- *Environmental Chemistry:* ESE 142, ESE/Ge/Ch 171, ESE/Ch/Ge 175 a
- *Environmental Physics:* ESE/Ge 148 ab

In cases of unusual preparation, students may petition to substitute an advanced elective course for a core course, but the substituted courses must be in the same area as the courses replaced. The remaining units required are to be fulfilled by taking additional core courses (not used to satisfy the core requirement) or elective courses in ESE or related disciplines. In recognition that solutions to environmental problems are limited not only by technical but also by social, political, and economic issues, students are encouraged to include relevant courses in the social sciences in their program of study. For recommended elective courses, see http://www.ese.caltech.edu/courses/electives.html. Not more than 42 units may be in reading and/or research (ESE 100, 200, 300) courses (these units are in addition to the required six units of ESE 101 and ESE 150 abc). Of these reading and/or research units, not more than 27 units may be taken during the first year of graduate study. Exceptions may be granted by petition. Courses may be taken at the Scripps Institution of Oceanography under the exchange arrangement described on page 246.

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 oral and written defense of two research propositions, supplemented by a written description of one of them. Written abstracts must be submitted for both propositions. Fundamental questions derived from the ESE core courses may also be included in the qualifying examination. Students are encouraged to consult with others concerning their ideas on propositions, but the material submitted must be the work of the student. There must be a different faculty member associated with each of the two propositions. It is expected that the student's research adviser will supervise the proposition for which the student prepares the written description. This written description will generally be in the form of a proposal but the student may submit a research paper instead. In preparation for the qualifying examination, students are encouraged to register for nine units of research (ESE 100) in their second and third terms of residence.

Advancement to Candidacy. Students are expected to advance to candidacy before the end of the first term of their third year of residency.

Thesis and Final Examination. Copies of the completed thesis must be provided to the examining committee two weeks before the examination. The final oral examination focuses on the work of the thesis and, according to the Institute regulations, must be held at least two weeks before the degree is conferred. In addition to the two copies of the final thesis required by the Institute, a third copy must be submitted to the option office.

Subject Minor
Students majoring in another option at the Institute may elect a subject minor in environmental science and engineering. They must obtain approval from the ESE option representative for a course of study containing at least 45 units of advanced ESE courses.

Geological and Planetary Sciences

Aims and Scope of the Graduate Program
Students in the Division of Geological and Planetary Sciences study the earth and planets to understand their origin, constitution, and development, and the effect of the resulting physical and chemical characteristics on the history of life, on the environment, and on humanity. Broad training in the fundamental sciences enriched by more specialized coursework within the division forms the basis of the educational program. Students are encouraged to work with complex and often incomplete data sets, to undertake research in natural settings such as in the field or at sea, and to use the many modern laboratory facilities available within the division. Programs of study and research are pursued in environmental science and engineering, geology, geobiology, geochemistry, 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 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—No
Geobiology—Submit the scores for any subject test

Geochemistry—Strongly recommended but not required
Geology—No
Geophysics—No
Planetary Science—Strongly recommended but not required.

Applicants from non-English-speaking nations are required to submit Test of English as a Foreign Language (TOEFL) scores.

Based on their applications and interests, students enter one of the major subject options of the division and are given an academic adviser who is a professorial faculty member associated with the option. The five options are geobiology, geochemistry, geology, geophysics, and planetary science. The division also jointly administers the environmental science and engineering option (see page 312). Students may later change options, but must first obtain approval by 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 by-product can be the formulation of propositions for the Ph.D. qualifying oral examination or orientation toward Ph.D. research.

Advising and Thesis Supervision

The academic adviser appointed after the first quarter for each incoming student continues 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 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 committee serve as advisers, counselors, and resources. Committee membership may be changed if a student's research interests change.

The thesis advisory committee meets with the student at least once each year for a progress review, and informally whenever the student needs or requests assistance or guidance. In addition, the faculty members in each option have their own systems for annual evaluations of student progress. A few months before completion of the thesis dissertation, the thesis examining committee will be chosen, usually including the members of the thesis advisory committee.

All students are urged to consult with division faculty in the following sequence if they have any problems: thesis and academic advisers, thesis advisory committee, option representative, academic officer, and division chair. If these division personnel cannot resolve a problem, then the student should turn to Institute offices.

Master's Degree

Students enrolled in the Ph.D. program may be awarded a master's degree when they have satisfied the basic Institute requirement of 135 units. These courses must be numbered 100 or higher, and must be part of those used to satisfy the Ph.D. requirement in one of the options of the division. Specifically required are Ge 109 and two courses from the list Ge 101, Ge 102, Ge 103, Ge 104, or ESE/Ge 148 a.

An application for admission to candidacy for an M.S. degree must be submitted to the Office of the Dean of Graduate Studies according to the academic calendar in the *Caltech Catalog* (see pages 4–5).

Doctoral Degree: Division Requirements

For a Ph.D. degree the student must 1) pass the qualifying oral examination, 2) satisfy course requirements of the division and of an option, and 3) complete a thesis and successfully defend it in a final oral examination. 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 staff 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 five options of the division. A more detailed outline of the qualifying examination is available on the division website.

Before the end of the second year, the thesis advisory committee will be selected, as outlined above.

The division encourages students to engage in research early in their graduate careers. Students making normal progress will submit to refereed journals papers that have been approved by a faculty member of the division. Doctoral candidates must complete a thesis and submit it in final form by May 10 of the year in which the degree is to be conferred. 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 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 five basic introductory courses Ge 101–104 and ESE/Ge 148 a, in areas in which the student has not had substantial training. Also required is one term of Ge 109. Throughout their graduate careers, students are expected to attend departmental seminars and seminar courses led by visiting scientists.

Requirements of the Major Subject Options

Geobiology. In addition to the general Institute and basic division requirements, candidates for the Ph.D. degree in geobiology must successfully complete a minimum of 90 units at the 100 or greater level, including Ge 104; either Bi/Ch 110 or ACM/ESE 118; and two courses from each of the following three subject menus.

Geology: Ge 106 ab, 112, 114 ab, 124.
Chemistry: ESE 142, Ge/ESE 143, 149, Ge 140, ESE/Ge/Ch 171, 172.
Biology: ESE/Bi 166, 168, Ge/ESE 170, Bi 117, ESE/Ge 148 c.

Other classes may be substituted for these menu requirements with the approval of the option representative. A student with substantial prior experience in geobiology (e.g., an M.S. degree) may use prior course work to substitute up to 45 of these units with the approval of the geobiology option representative. All students must have a basic knowledge of organic chemistry at the level of Ch 41 a. This requirement may be met by previous course work or through successful completion of this class.

Geochemistry. In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geochemistry are required to demonstrate an understanding of the field through a total of 90 units of course work at the 100 level or higher spread over four of the subdisciplines offered in the option: petrology/mineralogy, isotope geochemistry, cosmochemistry, water chemistry/oceans, atmospheres, and biogeochemistry. A student with substantial prior experience in some of the subdisciplines may use prior course work to substitute for up to 45 of these units with the approval of the geochemistry option representative. In the oral candidacy exam, the student will be subject to examination in all four of the chosen subdisciplines. All students must have a basic knowledge of chemistry at the level of Ch 21 and mathematics at the level of Ge 108.

Geology. The geology option requirements are (1) two of Ge 102, 103, 104, or ESE/Ge 148 a, which also satisfy the basic division requirement; (2) 36 units in 100-level science or engineering courses taken outside the GPS division, or in courses cross-listed with other divisions. Ch 21 abc may be included as part of these units, and other courses below the 100 level may be included at the discretion of the option representative; (3) 36 units of advanced field geology, in the form of three terms of Ge 121 abc taken from three different instructors; (4) an additional 18 units of 100- or 200-level courses within the GPS division. Courses that cannot be used to satisfy these requirements include research and reading courses, and certain courses constituting basic preparation in the field of geology, such as Ge 106, Ge 112, Ge 114 ab, and Ge 115 abc. 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 ACM/ESE 118 is required of all Ph.D. candidates in geology. Students entering the geology option with a master's degree in a science or mathematics may be exempt from up to 45 units at the discretion of the option representative.

Geophysics. In addition to general Institute and basic division requirements, candidates for the Ph.D. degree in geophysics must successfully complete the following course requirements: two of Ge 101, 103, 104, or ESE/Ge 148 a; either Ae/Ge/ME 160 ab, APh 105 ab, MS 115 ab or a subject equivalent; three of Ge 161, Ge 162, Ge 163, or Ge 164, and Ge 111 ab, and the choice between a minor in any field at Caltech or five additional 100- or 200-level science or mathematics courses. It is highly recommended that these courses be taken in the first year. 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 150), planetary interiors (Ge 131), and planetary surfaces (Ge 151). In addition, students shall successfully complete 45 units of 100-level or higher courses in a coherent field of specialization. This requirement may be satisfied by completion of a subject minor or through a set of courses chosen in consultation with and approved by the adviser and the option representative. All candidates are expected to possess knowledge of physics and mathematics at the level of Ph 106 and ACM 95. This requirement may be met by previous coursework or through successful completion of these classes.

Subject Minor

A student from another division of the Institute may, with the approval of the Division of Geological and Planetary Sciences, elect a minor in any one of the major subjects listed above. Such a subject minor will include at least 45 units in courses at the 100 level or higher. Normally, a member of the division faculty will participate in the student's oral thesis defense.

History

The program for a subject minor in history must be approved by the executive officer for the humanities before the admission to candidacy. In addition to meeting general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in history.

History and Philosophy of Science

Graduate students in science, mathematics, or engineering may take a minor in history and philosophy of science (HPS). The graduate minor is devoted to the study of the historical evolution and philosophical underpinnings of the physical and biological sciences. Historical work in the minor includes the origins of experimental practice, the social and institutional contexts of science, the origins and applications of quantitative methods, specific developments since antiquity in physics, biology, and chemistry, as well as biographical and comparative studies. Philosophical research deals with issues in causation, explanation, scientific inference, the foundations of probability and decision theory, philosophy of mind and psychology, philosophy of neuroscience, and scientific fraud and misconduct.

The minor thus fosters the acquisition of broad knowledge about the scientific enterprise and related foundational problems, as well as more detailed analysis of the progress of and philosophical problems in particular branches of science. It is a valuable supplement to a technical degree since it helps equip students to understand the nature of scientific progress and to grapple with the conceptual basis of science and its wider ramifications. Students who successfully complete the HPS minor will be recognized with official credit for the achievement on their transcripts.

Requirements

Graduate students who take an HPS minor are expected to complete Hum/H/HPS 10, HPS 102 ab, HPS/Pl 120, at least three units of HPS 103, and 18 units of additional work in HPS, to be completed by taking courses in HPS/H or HPS/Pl numbered 99 or higher. Students need not complete the requirements for the minor within the first two years of graduate study.

Materials Science

Aims and Scope of the Graduate Program

The graduate program is designed to give students an understanding of general phenomena in synthesis–structure–property relationships in all materials, plus a detailed understanding of phenomena for at least one particular class of materials. After completing the Ph.D. program, students will be qualified for 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 the 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.

Master's Degree
Each student is assigned to a member of the faculty, who will serve as the student's adviser. The adviser and option representative for materials science will approve his or her course of study.

Study for the degree of Master of Science in Materials Science will ordinarily require three terms of courses. The courses shall be chosen from the list of core courses below, although 27 units of research (MS 200 or equivalent) may be substituted for 27 units of lecture or laboratory courses. Completion of 138 units of these courses within two years with no grade less than a C constitutes the academic requirements for the M.S. degree.

Core Courses

1. MS 131, MS 132, MS 133.
2. APh 105 a or ChE/Ch 165, APh 105 b or ChE/Ch 164, MS 105.
3. Two quarters of courses focused on specific materials, such as APh 114 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; Ae/AM/CE 102 abc or Ae/Ge/ME 160 ab; Ch 120 a; Ch 121 ab.
5. 18 units of courses comprising either the third terms of the sequences taken in 3 and 4 above, or other courses appropriate for the student's research interests, such as MS 125, 142, MS/EST 143, MS/ME 161, 162.
6. Mathematics at the level expected of research in the student's field. This may be satisfied by the courses ACM 100, or AM 125 abc, or ACM 101 abc, or Ph 129 abc, or may be waived at the discretion of the student's adviser and option representative.
7. MS 110 abc (3 units) or APh 110 (2 units) or E 150 abc (3 units), seminar.

Degree of Doctor of Philosophy

Residency. Work toward the degree of Doctor of Philosophy in materials science requires a minimum of three years following the completion of the bachelor's degree or equivalent.

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. In the first year, each student shall 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 addition, each student who has passed the candidacy examination shall select a faculty mentor, who will review the student's progress at least annually.

Admission to or Continuation in Ph.D. Status. To be advanced to candidacy for the doctor's degree the student must satisfy three requirements:

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 must prove competency in these areas through an oral examination in each subject.
b. *Oral Candidacy Examination.* The student will prepare a brief presentation on a topic in his or her proposed area of research. The core of the examination is based on the student's course work and how it is related to the topic of the presentation. This examination should be taken no later than the end of the student's second year of residence.
c. *Research Competence.* The student must have a doctoral research adviser, and must have completed at least 18 units of MS 200.

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. It will consist of a public thesis seminar and an associated oral examination on the thesis and related fields. This examination will be held at least two weeks after the doctoral thesis has been presented in its final form, and prior to its approval. This examination must be taken at least four weeks before the commencement at which the degree is to be granted.

Subject Minor

A 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. Normally a member of the materials science faculty will participate in the candidacy examination in the student's major department.

Mathematics

Aims and Scope of the Graduate Program

The principal aim of the graduate program is to develop the student's ability to do original research in mathematics. Independent and critical thinking is fostered by direct contact with faculty members. (An indication of the current research interests of the faculty is found on page 117.) Faculty advisers help students plan their programs of study leading to a Ph.D. in mathematics. Entering students are advised by the director of the Ph.D. program, who assists them in selecting appropriate courses, depending upon their previous studies.

Course Program
The graduate courses are listed in section five. The three core courses—Ma 110 in analysis, Ma 120 in algebra, and Ma 151 in geometry and topology—are required of all graduate students unless excused by the director of the Ph.D. program. Students are expected to complete these core courses in preparation for the qualifying examinations (see below), usually in the first year. (Entering students are allowed to take a qualifying examination in September or October in order to demonstrate knowledge of one or more of the core areas. By passing the examination, they are excused from taking the corresponding course.) In addition, students are required to complete nine quarters of other advanced mathematics courses, at least two of which are in discrete mathematics: combinatorics, complexity, and computability, or logic and set theory. Under special circumstances (e.g., finishing the degree in three years), exceptions to these requirements may be granted by the director of the Ph.D. program.

Beginning no later than the second year, students will be expected to begin independent research work and will be strongly encouraged to participate in seminars.

Master's Degree
Entering graduate students are admitted directly to the Ph.D. program, since the Institute does not offer a regular program in mathematics leading to the master's degree. A master's degree may be awarded in exceptional circumstances either as a terminal degree or preliminary to the Ph.D. Sufficiently advanced undergraduates may be admitted to graduate standing to pursue a master's degree simultaneously with the bachelor's program.

The recipient of a master's degree will be expected to have acquired, in the course of studies as an undergraduate or graduate student, a comprehensive knowledge of the main fields of mathematics comparable to 180 units of work in mathematics with course numbers greater than 90.

The general Institute requirements specify that the recipient of a master's degree must have taken at least 135 units of graduate work as a graduate student at the Institute, including at least 81 units of advanced graduate work in mathematics. This advanced work is interpreted as work with a course number greater than 109 and may include a master's thesis.

Degree of Doctor of Philosophy
Qualifying Examinations. Qualifying examinations in the three core areas—analysis, algebra, and geometry/topology—are offered in October and June. These examinations emphasize mastery of the basic concepts and theorems and the ability to apply them to specific cases. Students are required to take and pass two of the three examinations, and for the one not taken, to complete the cor-

responding core course with a grade of B of better. Normally, the examination requirements are completed at the end of the first year or the beginning of the second.

Summer Study. Although there are no courses given in the summer, graduate students are expected to carry out studies and research in their chosen area of mathematics. In the summer after the first year, they will work under the guidance of a faculty member to investigate a possible area for their thesis research.

Thesis Adviser. It is expected that by the fall quarter of the second year, students will find a member of the faculty who agrees to serve as their thesis adviser. The progress of all continuing students is assessed by the faculty each fall, and students will consult with their advisers about their progress and planning of their studies and research.

Students receive help and advice not only from their thesis adviser and other faculty mentors, but also whenever needed from the director of the Ph.D. program, the executive officer, and the faculty ombudsperson in mathematics. (See also the section Guidelines for Graduate Student Advising on page 243.)

Admission to Candidacy. Before the end of their third year, students are expected to finish the process of applying for admission to candidacy for the Ph.D. degree. This formal step requires completion of the requirements for qualifying examinations and core courses, as well as a satisfactory oral presentation to a committee of faculty members. The presentation will describe both the general area of the student's proposed thesis research and the specific problem or problems to be addressed. A written summary of the presentation, typically 3–10 pages, must be given to the committee members at least one week before the presentation. The student and his or her adviser will arrange the formation of this committee, which will have three members, including the adviser.

Thesis and Final Examination. On or before the first Monday in May of the year in which the degree is to be conferred, candidates for the degree of Doctor of Philosophy must deliver copies of their theses to their advisers, to the Graduate Office, and to the members of the committee that will conduct the final oral examination on the thesis. The examination must be held at least three weeks before the date on which the degree will be conferred and at least two weeks after the delivery of the copies of the thesis.

Subject Minor

Students majoring in other fields may take a subject minor in mathematics. Minor programs must include 54 units of advanced work approved by a representative of the mathematics department, who will ensure that the work represents a concentrated study in one or more of the main fields of mathematics. A special oral examination in the subject minor will be given soon after completion of the minor program.

Travel Grants
Special funding is available to graduate students to attend conferences and workshops in the United States or abroad (please see Bohnenblust Travel Grants on page 260).

Mechanical Engineering

Aims and Scope of the Graduate Program
The aim of the graduate program in mechanical engineering at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, and a strong background in the basic and engineering sciences, with laboratory and design experience. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Original research in mechanical engineering is an essential component of the graduate program. Independent and critical thinking is encouraged by participation in seminars and by discussions with faculty members. Research groups in mechanical engineering are small, creating an environment where students work closely and collaboratively with the faculty.

The degrees of Master of Science, Mechanical Engineer, and Doctor of Philosophy are offered.

Research areas in mechanical engineering at Caltech include mechanics (including active materials, fracture mechanics, and mechanics of materials), mechanical systems (including control and analysis of dynamic systems, engineering design of electromechanical systems, design theory and methodology, kinematics, optimization, robotics, and structural design), and fluid and thermal systems (including acoustics, cavitation, chemical vapor deposition, combustion, fluid flow, heat and mass transport, multiphase and multicomponent flows, propulsion, and turbulence). Research in these areas is applied to a wide variety of problems including control of aircraft engines, design of vehicle structures, granular flows, hyper-redundant robots, jet noise reduction, locomotion and grasping, medical applications of robotics, navigation algorithms, structured design of micro-electro-mechanical systems (MEMS), thin film deposition, transportation systems, propulsion systems, explosion dynamics including deflagrations, detonations, and shock waves, and rapid assessment of early designs.

Admission
As preparation for advanced study and research, entering graduate students must have a thorough background in undergraduate mathematics, physics, and engineering. An outstanding four-year undergraduate program in mathematics and sciences may be substituted for an undergraduate engineering course, with the approval of the faculty. 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. However, in every case the student will be urged to take some courses that will broaden his or her understanding of the overall field, as well as courses in the specialty. Most graduate students are also required to take further work in applied mathematics.

Master's Degree

The degree of Master of Science in mechanical engineering provides the student with advanced training beyond the undergraduate fundamentals, and may include an introduction to research. A minimum of 138 units of courses numbered 100 or above, that meet the distribution requirements 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. Each student's program must be approved by the option representative in mechanical engineering.

Required Program

- Graduate Mechanical Engineering core—54 units
  These units should provide a solid base for the student's engineering interest. The courses may be selected from the following list: Ae/APh/CE/ME 101 abc, Ae/Ge/ME 160 ab, ME 118, ME 119 ab, Ae/ME 120 ab, Ae/AM/CE 102 abc, AM/CE 151 ab or CDS 140 ab; and CDS 110 ab.
- Mathematics, Engineering, and Research electives—54 units
  Students who have not taken the equivalent of ACM 100 abc are required to take ACM 100 abc for 36 units. Mechanical engineering students are urged to consider taking 27 units of courses in automation and robotics (ME 115 ab, ME 131, ME/CS 132); engineering design (ME 171); multi-phase flows (ME 202 abc); propulsion (Ae 121 abc); experimental methods (Ae/APh 104 abc); or any additional courses listed in the Graduate Mechanical Engineering courses. Other courses may also be taken in Ae, AM, ACM, ME, JP, MS, EE, ESE, APh, CDS, CS, ChE, CNS. Students who are considering study beyond the master's degree are encouraged to take research units, ME 300, up to a maximum of 27.
- Free Electives—27 units. These units may be selected from any course with a number of 100 or greater, except that research units may not be included.
- Engineering Seminar, ME 150 abc—3 units.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree should also read the section below relating to this degree.

Degree of Mechanical Engineer

Greater specialization is provided by work for the engineer's degree than by work for the master's. The degree of Mechanical Engineer is considered to be a terminal degree for the student who desires more highly specialized advanced training with less emphasis on research than is appropriate to the degree of Doctor of Philosophy. However, research leading to a thesis is required for both degrees. The student should refer to Institute requirements for the engineer's degree.

Not less than 55 units of work shall be for research and thesis; the exact number shall be determined by a supervising committee, appointed by the dean of graduate studies. Courses should be closely related to mechanical engineering. The specific courses (to be taken and passed with a grade of C or better by the candidate) will be finally determined by the supervising committee. The courses must include an advanced course in mathematics or applied mathematics, such as AM 125 abc or ACM 101 abc, that is acceptable to the faculty in mechanical engineering. A suitable course program may usually be organized from the more advanced courses listed under Ae, AM, ACM, CDS, JP, ME, and MS.

Degree of Doctor of Philosophy

The Ph.D. degree in mechanical engineering is focused on research, and prepares students to develop new understanding and advanced technology to address contemporary problems. 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. 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 additional years are usually needed for preparation of the dissertation.

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. dissertation supervision committee within one year 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 engineering. The adviser shall serve as chair of this committee. This committee shall meet as requested by the student. Further, this 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 supervision 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 and form a three-member dissertation supervision committee with the adviser as the chair.
- Successfully complete at least 54 units of research and demonstrate satisfactory research progress.
- Pass with a grade of at least C a minimum of 18 units of course work in any three core mechanical engineering subjects spanning at least two broad areas listed below. Examples of suitable courses are given in parentheses.

Area 1
Fluid Mechanics (Ae/APh/CE/ME 101 abc)
Mechanics of Structures and Solids (Ae/AM/CE/ME 102 abc)
Continuum Mechanics of Solids and Fluids (Ae/Ge/ME 160 ab)

Area 2
Thermodynamics and Statistical Mechanics (ME 118, APh 105, Ch/ChE 164, Ch 166)
Heat and Mass Transfer (ME 119 ab)
Combustion (ME 120 ab)

Area 3
Dynamical Systems (AM/CE 151 ab or CDS 140 ab)
Mechanical Systems and Design (ME 115 ab, ME 171, ME 175)
Controls (CDS 110 ab, CDS 212)

The student may petition the mechanical engineering faculty to accept alternate subjects or areas. These changes should retain core mechanical engineering knowledge and represent sufficient breadth. The petition must be submitted to the option representative and approved before the student registers for the course.

These 54 units may also be used in the student's program for the master's degree. Students must do the following:

- Pass with a grade of at least C an additional 54 units (with a course number above 100) that pertain to the student's specialty and are approved by the dissertation supervision committee in engineering or science.
- Pass with a grade of at least C 27 units of advanced courses in mathematics or applied mathematics chosen in consulta-

tion with their adviser from the following list: ACM 101 or higher, AM 125, CDS 201, CDS 202, Ma 108 or higher, Ph 129. The requirement in mathematics is in addition to the requirements above and cannot be counted toward a minor.

- Pass both subject and research components of the oral candidacy examination. 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. The oral candidacy examination must be taken before the end of the second year of graduate academic residence at the Institute.

The requirement of a minimum grade of C will be waived for an advanced course which (i) lists one of the courses in Areas 1, 2, and 3 as a prerequisite, and (ii) is offered only pass/fail.

If the student elects to take a subject minor, these units cannot be used to satisfy any of the Ph.D. degree requirements in mechanical engineering.

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 candidacy for the Ph.D. degree.

Registration beyond Fifth Year of Graduate Residence. The annual approval of the Ph.D. dissertation supervision committee is necessary for registration beyond the fifth year 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 will be a public seminar presented by the candidate, with an open question period, followed by a private examination by the examining committee. The examining committee shall consist of at least four Caltech professorial faculty members, at least three of whom shall be from the Division of Engineering and Applied Science, and at least two of whom shall be mechanical engineering faculty members. One member of the committee shall be from outside the student's area of Ph.D. research. The student's adviser shall act as chair of the committee.

Subject Minor

A student majoring in another branch of engineering or another division of the Institute may, with the approval of the faculty in mechanical engineering and the faculty in his or her major field, elect mechanical engineering as a subject minor. The program of courses must differ markedly from the major subject of study or research, and must consist of at least 54 units of advanced work. The student must also pass an oral examination that is separate from the examination in the student's major.

Physics

Aims and Scope of the Graduate Program

The physics option offers a program leading to the degree of Doctor of Philosophy. This program prepares students for careers in scientific research or research combined with teaching, and so its most important part is independent research. Courses are offered that give a broad treatment of both fundamental physics and specialized physics research topics. These are intended both to help a beginning graduate student prepare for research and to broaden an advanced student's knowledge of physics. Caltech research opportunities include elementary particle physics, nuclear physics, cosmic-ray, gamma-ray, and X-ray astronomy, submillimeter astronomy, condensed-matter physics, atomic/molecular/optical physics, quantum optics, applied physics, gravitational physics, cosmology, astrophysics, mathematical physics, biophysics, and theoretical physics.

A Master of Science degree may be awarded upon completion of a program of courses. Students are not normally admitted to work toward the M.S. in physics unless they are also working toward a Ph.D.

Admission

Application forms for admission to graduate standing and for financial assistance can be obtained from the Office of the Dean of Graduate Studies, California Institute of Technology, Pasadena, CA 91125, or can be downloaded from http://www.gradoffice.caltech.edu. Completed applications should reach the Graduate Office by January 15. Applicants are strongly advised to take the Graduate Record Examination (GRE) and the Advanced Physics Test. Information can be obtained from the Educational Testing Service, 20 Nassau Street, Princeton, NJ 08540 (http://www.ets.org).

Placement Examinations

Students admitted to work for an advanced degree in physics are required to take placement examinations, typically given the Monday of general orientation week before the student's first term of graduate study. These informal exams are used as a guide in selecting the proper course of study. The exams cover material in classical mechanics, electromagnetism, quantum mechanics, statistical mechanics, and mathematical physics. In general, they will be designed to test whether the student possesses an understanding of general principles and the ability to apply these to concrete problems, rather than detailed informational knowledge. The results of the placement exams are not formally recorded as a part of the student's record. In cases in which there is a clear basis for ascertaining the status of the entering graduate student, the placement exams may be waived.

Master's Degree

A Master of Science degree in physics will be awarded, upon request, to physics Ph.D. students who have completed the oral and written candidacy examinations. Alternatively, a master's degree will be awarded to any Caltech graduate student in good standing upon satisfactory completion of a program approved by the option representative that fulfills the following requirements:

Ph 125 abc (If this course, or its equivalent, was taken as part of an undergraduate program, it may be replaced by 27 units of any quantum-mechanics-based course.)	27 units
Physics electives These must be selected from Ph 103, Ph 105, Ph 118, Ph 127, Ph 129, Ph 135, Ph 136, or physics courses numbered 200 or above.	81 units
Other electives These must be graduate courses from physics or any other option, including the humanities.	27 units

Substitutions of other graduate courses in place of the above requirements must be approved by the option representative.

Degree of Doctor of Philosophy

In addition to the general Institute requirements for a Ph.D., the particular requirements for a doctorate in physics include admission to candidacy as described below, writing a thesis that describes the results of independent research, and passing a final oral examination based on this thesis and research. Physics graduate students may exercise the pass/fail option on any and all courses taken.

Admission to Candidacy. To be admitted as a candidate for a Ph.D., a student must pass two terms of Physics Seminar (Ph 242), pass written candidacy examinations covering basic physics, satisfy the Advanced Physics requirements described below, and pass an oral candidacy examination. These requirements are designed to ensure that students have an adequate preparation in the basic tools of physics, as well as a broad general knowledge of advanced physics.

Basic Physics Requirement. To be admitted to candidacy, physics students must demonstrate proficiency in all areas of basic physics, including classical mechanics (including continuum mechanics), electricity and magnetism, quantum mechanics, statistical physics, optics, basic mathematical methods of physics, and the physical origin of everyday phenomena. A solid understanding of these fundamental areas of physics is considered essential, so proficiency will be tested by written candidacy examinations.

No specific course work is required for the basic physics requirement, but some students may benefit from taking several of the basic graduate courses, such as Ph 106, Ph 125, and Ph 127. A syllabus describing the exam contents will be available, and students are encouraged to study independently for the exams, rather than taking a heavy load of basic physics courses.

The written exams are offered at frequent intervals, typically once per term, and the separate sections 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 participating in a research group.

Advanced Physics Requirement. In addition to demonstrating a proficiency in basic physics, students must also establish a broad understanding of modern physics through study in six of the following eight areas of advanced physics:

1. elementary particle physics
2. nuclear physics
3. atomic/molecular/optical physics
4. condensed-matter physics
5. gravitational physics
6. astrophysics
7. mathematical physics
8. interdisciplinary physics (e.g., biophysics, applied physics, chemical physics)

The advanced physics requirement can be fulfilled by passing exams in the separate areas, or by passing courses. Each area is meant to be covered by the equivalent of a one-term course. There will be a list of course substitutions for each of the areas, which will include courses outside of physics. Other courses may be substituted with permission from the Physics Graduate Committee.

Oral Candidacy Exam. This exam is primarily a test of the candidate's suitability for research in his or her chosen field. The chair of the examination committee will be the professor the student plans to do research with, and normally the student will have already begun research (Ph 172 or Ph 173) on a definite topic with that professor. The examination will cover the student's research work and its relation to the general field of specialization. Before being allowed to take this exam, a student must have satisfied all the other requirements for admission to candidacy.

Research Requirements. There are no specific research requirements, but in general a substantial effort is required to master the techniques in a given field and carry out a significant piece of original research. Students are strongly advised to start doing part-time research as soon as possible, and to carry it on in parallel with formal course work, taking reading and research units (Ph 171–173) prior to being admitted to candidacy. Typically, students continue graduate study and research for about two years after admission to candidacy.

Scheduling. Although students are encouraged to begin doing research soon after arriving at Caltech, they should also try to complete the requirements for candidacy as quickly as possible before focusing completely on a particular research area. Thus Ph 242 should be taken by all students in their first year of graduate study. The written candidacy exams should be attempted by the end of a student's first year of study, and be passed by the end of the second year. The Advanced Physics requirements should also be completed by the end of the second year, but may be extended into the third year depending on the availability of specific courses. If these deadlines are not met, a student must petition the Physics Graduate Committee before registration for subsequent terms will be allowed.

Advising and Thesis Supervision. After taking the placement exams described above, physics graduate students meet with the chair of the admissions committee to decide on a first-year course schedule. At this time it is appropriate for students, especially those admitted with GRAs, to consult with the admissions chair, the option representative, the executive officer, and/or individual faculty members to select a tentative research group, if this hasn't already occurred over the summer. At any time, a student may consult with the option representative concerning such matters as advising and switching research groups. When the student is ready to form his or her candidacy committee, this is done in consultation with the executive officer. This committee, besides examining the student's knowledge of his or her chosen field, will consider the appropriateness and scope of the proposed thesis research. Supervision of the thesis research is the responsibility of the thesis adviser, and the student should maintain close contact with his or her adviser. In some circumstances, such as interdisciplinary work with an adviser from another department, a special committee may be formed to follow the progress of the research as well.

The Minor. A minor is not required, but a student may elect to pursue a minor in another option.

Language Requirements. There are no language requirements for a Ph.D. in physics.

Thesis and Final Examination. A final oral examination will be given not less than two weeks after the thesis has been presented in final form. This examination will cover the thesis topic and its relation to the general body of knowledge of physics. The candidate is responsible for completing the thesis early enough to allow the fulfillment of all division and Institute requirements, with due regard for possible scheduling conflicts.

Subject Minor

Students desiring a subject minor in physics should discuss their proposed program with the chair of the Physics Graduate Committee. Forty-five units are required for approval of a subject minor in physics. Physics courses with numbers over 100 will be allowed for the subject minor. At least 18 of the 45 units must be chosen from the physics electives list (see list under *Master's Degree in Physics*), excluding Ph 129 and any specific courses in physics required for the student's major program. An oral exam may be required by the Physics Graduate Committee. This exam will include both academic topics and topics on current physics research areas. The oral exam may be waived if at least one term of Ph 242 has been taken successfully, or if all 45 units are in letter-graded (*not* pass/fail) courses.

Social Science

Aims and Scope of the Graduate Program
The Caltech Ph.D. program in social science 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. Most graduates of the program work in departments of economics, political science, or public policy, or in business schools at major universities. Others have taken positions as economic analysts, program evaluators, and planners in both the public and private sectors. In addition, a special program enables students to obtain joint degrees in social science from Caltech and in law from other nearby universities. Graduates of this joint program teach in law schools, practice law, and hold other positions in academia and government.

Master's Degree
Entering graduate students are admitted to the Ph.D. program, and will earn the M.S. degree after successful completion of 135 units of course work. The program does not admit students who plan to obtain an M.S. degree only, but a student who does not go on to achieve a Ph.D. may leave with a terminal master's degree.

Admission
Admission to the Caltech Ph.D. program is highly competitive, and those who are admitted have excellent GRE scores, impressive academic records as undergraduates, and highly supportive letters of recommendation. Entering students are expected to have a strong background in mathematics, and to have completed courses in calculus at the levels of Ma 2, linear algebra, and mathematical statistics. A course in real analysis is also highly desirable. Students are expected to take additional mathematics courses when relevant to their research.

Course Program
The program is designed to enable students to earn their Ph.D. in five years, although it is sometimes possible to finish in four years. During their initial two years in the program, students are expected to acquire competence in the core areas of economics, analytical

politics, and econometrics. In the third year students are expected to begin their dissertation research while they continue to acquire skills. The fourth and fifth years are devoted to research and writing, culminating in the Ph.D. dissertation and the granting of a Ph.D.

The first-year curriculum consists of the following four three-quarter course sequences: decision theory, game theory, and social choice (SS 201 abc); political institutions and political behavior (SS 202 abc); foundations of economics (SS 205 abc), and econometrics (SS 222 abc). All courses are nine units each, so students must register for at least 36 units each quarter. In order to make satisfactory progress, students must complete each class with a grade of B or better. The DGS reviews each student's progress at the end of every quarter.

Second-year courses provide additional training in various subfields of social science, and are designed to teach students how to conduct independent research. Many courses are designated as "workshop" courses, which are coordinated two- or three-quarter sequences in particular subfields. The sequential workshop courses are designed to provide the skills and knowledge that students need to conduct independent research and to effectively present their findings. In these courses instructors may require a paper or project to be completed by the end of each quarter, but they may instead have students submit a more substantial paper at the end of the course sequence. Students are expected to take at least two workshop course sequences. These should be chosen in consultation with faculty members working in the area in which the student wishes to do thesis research. Workshop courses that are offered every year include Foundations of Political Economy (SS 210 abc), Advanced Economic Theory (SS 211 abc), Applications of Microeconomic Theory (SS 212 abc), Identification Problems in the Social Sciences (SS 227 abc), American Politics (SS 231 abc), and Experimental Methods of Political Economy (SS 260 abc). Courses that are offered frequently, but not necessarily every year, include Financial Economics (SS 213 abc), Advanced Topics in Econometric Theory (SS 223 abc), Theoretical and Quantitative Dimensions of Historical Development (SS 229 abc), and Historical and Comparative Perspectives in Political Analysis (SS 232 abc). Students who choose to pursue economic theory may fulfill workshop course requirements by taking a sequence of courses in mathematics, such as Classical Analysis (Ma 108), Analysis (Ma 110), Functional Analysis (Ma 140), Probability Theory (Ma 144), or Convex Analysis and Economics (Ec 181). As in the first year, all classes offered for grades must be completed with a grade of B or better. SS 300 must be completed with a grade of pass. Students may take independent reading and study courses, but during the second year such courses do not count toward the 36 units per quarter requirement.

During the spring quarter of the second year students should enroll in SS 300, a seminar devoted to work on their second-year paper, and the Graduate Social Science Writing Seminar (SS 281), which focuses on scholarly writing and presentation. SS 300 is taken on a pass/fail basis. By the end of their second year each student is required to submit a research paper to the DGS. This paper must be approved by two members of the Caltech social science faculty.

During the first and second quarters of their third year, students take 15 units of Research in Social Science (SS 300), supervised by their primary adviser, and at least two other nine-unit courses. One of these courses is Modern Topics in Social Science (SS 280). This course exposes students to influential works in areas of social science that are not typically covered in the first- and second-year courses. In the third quarter students must enroll in at least one nine-unit course along with 24 units of SS 300. Beginning in their third year and in all subsequent years, all students should also enroll in the three-unit graduate student seminar (SS 282) every quarter. Every student must make a presentation in this class at least once a year. SS 300, 280, and 282 are all taken on a pass/fail basis.

The fourth year is a yearlong thesis workshop, which means students need to register for 33 units of SS 300 and three units of the graduate student seminar SS 282, all on a pass/fail basis.

During their fifth and final year in the program, students focus on obtaining a job and on completing and defending their dissertation. Early in the first term, students need to complete a job-market paper, practice presenting that paper, and assemble and mail job applications.

Progress Review Leading to Candidacy

At the end of the third quarter of the first year, students are required to take a written preliminary examination which has four components, each corresponding to one of the four course sequences of the first-year curriculum. The results given are honors, pass, and fail. Students must achieve at least a pass in all four parts of the exam. Failure to do so may lead to termination from the program, but the faculty may also decide to give students who fail the opportunity to retake any or all parts of the exam before the beginning of the second year.

Students must complete a research paper, which can be co-authored, by the end of the spring term of the second year. The DGS will appoint two faculty members, normally their primary adviser and second committee member, to monitor and evaluate progress on the second-year paper. If the two faculty reviewers find that a student's second-year paper is satisfactory, the student advances to the third year. If they do not, the social science faculty as a whole will decide whether or not the paper is satisfactory. If they decide it is not, they may also vote to terminate the student from the program.

Third-year students must write a research paper and present it to the faculty by the end of the third quarter. The paper cannot be coauthored, but should be worked on in consultation with and under the direction of the student's adviser. The paper and the presentation must demonstrate to the faculty that the student is capable of undertaking original research and presenting it to a scholarly audience. Ideally the third-year paper leads directly into dissertation research, but it is not a requirement that this be the case.

After the 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. At this point students need to file candidacy papers with the dean of graduate studies. If the evaluation is unfavorable, the student may be terminated from the program.

Organization of Thesis Committee

By February 1 of their second year, students should have decided upon the general area of social science in which they intend to pursue research and should therefore select a primary adviser whose work is related to their research interests. The adviser must be a member of the social science faculty at Caltech. The primary adviser will serve as chair of their dissertation committee. It is possible to change advisers if a student's research interests change. A second committee member, who must also be a member of the social science faculty, should be chosen by June 1 of the second year.

By the end of the third year, all students, in consultation with their advisers, should select a third committee member. This choice should be based on the content of ongoing dissertation research. It is not necessary that the third member be responsible for the full breadth of research covered by the dissertation, and in many cases the third member is selected to provide specialized help, e.g., in econometrics. Committee members may be chosen from outside the social science faculty, but such choices must be approved by the DGS. Students who are close to completing their dissertation must notify the division chairman, who will select a fourth member of the committee. The fourth member may be a member of the social science faculty, but may also come from outside the division or from another university. If the fourth member of the committee is from another university, the division will cover the cost of travel to and from Caltech for the oral defense.

Degree of Doctor of Philosophy

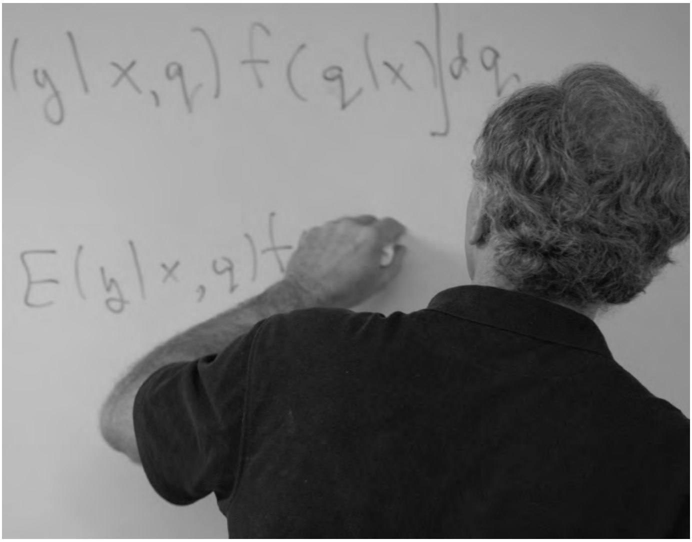
By November 1 of the fourth year all students are required to provide the DGS with a dissertation prospectus that reviews the relevant literature, outlines the student's proposed dissertation work, and presents a tentative schedule detailing when components of the dissertation are expected to be completed. This prospectus must be approved by the adviser and the second and third committee members in the fall of the fourth year and must be filed with the DGS.

By April 1 of the fourth year all students are required to convene a thesis proposal seminar with their adviser and other committee members. In this seminar they are to report on the current status of their dissertation research and outline a plan and timeline for completing it. Students and their committee should thus reach a clear, mutual understanding as to what additional work needs to be done to complete and to successfully defend their dissertation. While the committee chair/adviser is primarily responsible for monitoring progress on the dissertation, students also need to consult regularly with the other members of their committee and keep them informed as to the progress they are making and any problems they are encountering. It is also expected that in the fall of their fifth year, students will present an optionwide seminar in order to prepare for the job market.

After the dissertation has been completed, students, in consultation with their adviser, must schedule the oral defense. Students must provide a written copy of their dissertation to the DGS at least two weeks prior to the oral defense date. The dissertation is expected to represent publishable, original research with a coherent theme. Successful completion implies that the faculty has certified that the student is a trained, professionally knowledgeable, and potentially productive scholar in his or her chosen area of work.

Section Five

Courses



Courses numbered below 100 are taken primarily by undergraduate students. Those numbered from 100 to 199 are taken by both undergraduates and graduates, and those numbered 200 and above are taken primarily by graduate students.

The school year is divided into three terms. The number of units assigned in any term to any subject represents the number of hours spent in class, in laboratory, and estimated to be spent in preparation per week. In the following schedules, figures in parentheses denote hours in class (first figure), hours in laboratory (second figure), and hours of outside preparation (third figure).

At the end of the seventh week of each term, a list of courses to be offered the following term is published by the Registrar's Office. On the day of registration (see Academic Calendar), an updated and revised course schedule is published announcing the courses, class hours, and room assignments for the term. Students may not schedule two courses taught at the same time.

Abbreviations

Ae	Aerospace
An	Anthropology
ACM	Applied and Computational Mathematics
AM	Applied Mechanics
APh	Applied Physics
Art	Art History
Ay	Astrophysics
BMB	Biochemistry and Molecular Biophysics
BE	Bioengineering
Bi	Biology
BEM	Business Economics and Management
ChE	Chemical Engineering
Ch	Chemistry
CE	Civil Engineering
CNS	Computation and Neural Systems
CS	Computer Science
CDS	Control and Dynamical Systems
Ec	Economics
EE	Electrical Engineering
EST	Energy Science and Technology
E	Engineering
En	English
ESL	English As a Second Language
ESE	Environmental Science and Engineering
F	Film
Ge	Geological and Planetary Sciences
H	History
HPS	History and Philosophy of Science
Hum	Humanities
ISP	Independent Studies Program
IST	Information Science and Technology
L	Languages
Law	Law
MS	Materials Science
Ma	Mathematics
ME	Mechanical Engineering
Mu	Music
PA	Performance and Activities
Pl	Philosophy
PE	Physical Education
Ph	Physics
PS	Political Science
Psy	Psychology
SS	Social Science

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 18, and ME 19 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; acoustics. Instructors: Meiron, Pullin.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisite: ME 35 abc or equivalent.* Static and dynamic stress analysis. Two- and three-dimensional theory of stressed elastic solids. Analysis of structural elements with applications in a variety of fields. Variational theorems and approximate solutions, finite elements. A variety of special topics will be discussed in the third term such as, but not limited to, elastic stability, wave propagation, and introductory fracture mechanics. Instructor: Daraio.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6) first term; (1-3-5) second, third terms. Prerequisites: ACM 95/100 abc or equivalent (may be taken concurrently), Ae/APh/CE/ME 101 abc or equivalent (may be taken concurrently).* Lectures on experiment design and implementation. Measurement methods, transducer fundamentals, instrumentation, optical systems, signal processing, noise theory, analog and digital electronic fundamentals, with data acquisition and processing systems. Experiments (second and third terms) in solid and fluid mechanics with emphasis on current research methods. Instructor: McKeon.

Ae 105 abc. Aerospace Engineering. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 or ME 18 and ME 19 or equivalent. Ae 101 and 102 may be taken concurrently.* Part a: fundamentals of aerospace engineering and mechanics, launch vehicles and systems, rocket and space propulsion fundamentals, orbital mechanics and astrodynamics, trajectory and orbit design and maintenance, launch ascent and planetary reentry aerodynamics. Part b: spacecraft mechanical, structural, and thermal design; power in space; space environment and survivability; spacecraft and payload design; communications. Part c: space mission analysis and design, space logistics and reliability, mission and life-cycle cost analysis, and space systems integration. Student team projects focusing on a mission design study during third term. Instructor: Pellegrino.

CE/Ae/AM 108 abc. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

Ae 115 ab. Spacecraft Navigation. *9 units (3-0-6); first, second terms. Prerequisite: CDS 110 a.* This course will survey all aspects of modern spacecraft navigation, including astrodynamics, tracking systems for both low-Earth and deep-space applications (including the Global Positioning System and the Deep Space Network observables), and the statistical orbit determination problem (in both the batch and sequential Kalman filter implementations). The course will describe some of the scientific applications directly derived from precision orbital knowledge, such as planetary gravity field and topography modeling. Numerous examples drawn from actual missions as navigated at JPL will be discussed. Not offered 2009–10.

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 2009–10.

Ae 121 abc. Space Propulsion. *9 units (3-0-6); each term. Open to all graduate students and to seniors with instructor's permission.* Modern aspects of rocket, electrical, and nuclear propulsion systems and the principles of their application to lifting, ballistic, and spaceflight trajectories. Combustion and burning characteristics of solid and liquid propellants, liquid-propellant fuel systems, and combustion instability. Fundamentals of electric propulsion including ion thrusters, MHD, Hall effect, and arcjets. Introduction to spacecraft station-keeping, stability, and control. 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: Ravichandran.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6).* For course description, see Electrical Engineering.

Ae 159. Space Optical System Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 2, EE/Ae 157, or equivalent; APh 23 desirable.* Introduction to optical system engineering for remote sensing from space will be presented. End-to-end optical systems are discussed within the framework of the 10 scientific/technical disciplines required to build a successful system: optical engineering, physical optics of materials, solid-state physics/detectors, mechanics and mechanisms engineering, wavefront sensing and control, structures and dynamics, thermal engineering, spacecraft engineering, psychology of vision and software processing of images, and end-to-end system validation and calibration. Emphasis will be on the development of optical engineering tools. Not offered 2009–10.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6); first, second terms.* Elements of Cartesian tensors. Configurations and motions of a body. Kinematics—study of deformations, rotations and stretches, polar decomposition. Lagrangian and Eulerian strain velocity and spin tensor fields. Irrotational motions, rigid motions. Kinetics—balance laws. Linear and angular momentum, force, traction stress. Cauchy's theorem, properties of Cauchy's stress. Equations of motion, equilibrium equations. Power theorem, nominal (Piola-Kirchoff) stress. Thermodynamics of bodies. Internal energy, heat flux, heat supply. Laws of thermodynamics, notions of entropy, absolute temperature. Entropy inequality (Clausius-Duhem). Examples of special classes of constitutive laws for materials without memory. Objective rates, corotational, convected rates. Principles of materials frame indifference. Examples: the isotropic Navier-Stokes fluid, the isotropic thermoelastic solid. Basics of finite differences, finite elements, and boundary integral methods, and their applications to continuum mechanics problems illustrating a variety of classes of constitutive laws. Instructor: Lapusta.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5); second, third terms. Prerequisite: Ae/AM/CE/ME 102 a or ME 65.* Introduction and fabrication technology, elastic deformation of composites, stiffness bounds, on- and off-axis elastic constants for a lamina, elastic deformation of multidirectional laminates (lamination theory, ABD matrix), effective hygrothermal properties, mechanisms of yield and failure for a laminate, strength of a single ply, failure models, splitting and delamination. Experimental methods for characterization and testing of composite materials. Design criteria, application of design methods to select a suitable laminate using composite design software, hand layup of a simple laminate and measurement of its stiffness and thermoelastic coefficients. Instructor: Pellegrino.

Ae 200. Advanced Research in Aerospace. *Units to be arranged.* Ae.E. or Ph.D. thesis level research under the direction of the staff. A written research report must be submitted during finals week each term.

Ae 201. Advanced Fluid Mechanics. *9 units (3-0-6); second term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM 101 abc (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. Instructor: Meiron, Pullin.

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. Only part b offered 2009–10. Instructor: Gharib.

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. Instructor: Ravichandran.

Note: The following courses, with numbers greater than 209, are one-, two-, or three-term courses offered to interested students. Depending on conditions, some of the courses may be taught as tutorials or reading courses, while others may be conducted more formally.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE/ME 102 abc (concurrently) or equivalent and instructor's permission.* Analytical and experimental techniques in the study of fracture in metallic and non-metallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of nontraditional materials. Fatigue crack growth and life prediction techniques will also be discussed. In addition, "dynamic" stress wave dominated, failure initiation growth and arrest phenomena will be covered. This will include traditional dynamic fracture considerations as well as discussions of failure by adiabatic shear localization. Instructor: Ravichandran.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: AM 125 abc or equivalent; ACM 100 abc or equivalent; CE/AM/Ae 108 abc or equivalent or instructor's permission; Ae/AM/CE/ME 102 abc or equivalent; Ae/Ge/ME 160 ab desirable or taken concurrently.* Introduction to the use of numerical methods in the solution of solid mechanics and materials problems. First term: geometrical representation of solids. Automatic meshing. Approximation theory. Interpolation error estimation. Optimal and adaptive meshing. Second term: variational principles in linear elasticity. Finite element analysis. Error estimation. Convergence. Singularities. Adaptive strategies. Constrained problems. Mixed methods. Stability and convergence. Variational problems in nonlinear elasticity. Consistent linearization. The Newton-Rahpson method. Bifurcation analysis. Adaptive strategies in nonlinear elasticity. Constrained finite deformation problems. Contact and friction. Third term: time integration. Algorithm analysis. Accuracy, stability, and convergence. Operator splitting and product formulas. Coupled problems. Impact and friction. Subcycling. Space-time methods. Inelastic solids. Constitutive updates. Stability and convergence. Consistent linearization. Applications to finite deformation viscoplasticity, viscoelasticity, and Lagrangian modeling of fluid flows. Instructor: Ortiz.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6); first term. Prerequisites: ACM 100 abc or AM 125 abc; Ae/AM/CE/ME 102 abc.* Fundamentals of theory of wave propagation; plane waves, wave guides, dispersion relations; dynamic plasticity, adiabatic shear banding; dynamic fracture; shock waves, equation of state. Not offered 2009–10.

Ae 220 ab.Theory of Structures. *9 units (3-0-6); first, second terms.* Geometry of spatial curves; finite 3-D rotations; finite deformations of curved rods; dynamics of rods; strings and cables; theory of plastic rods; statistical mechanics of chains; applications including frames and cable structures, polymers, open-cell foams, DNA mechanics, cell mechanics; small strain and von Karman theory of plates; applications to thin films, layered structures, functionally graded thin films, delamination, plastic collapse; surface geometry; finite deformations of shells; dynamics of plates and shells; membranes; theory of plastic plates and shells; fracture of plates and shells; elastic and plastic stability; wrinkling and relaxation; applications including solar sails, space structures, closed-cell foams, biological membranes; numerical methods for structural analysis; discrete geometry; finite elements for rods, plates and shells; time-integration methods; thermal analysis. Not offered 2009–10.

Ae/CE 221. Space Structures. *9 units (3-0-6); third 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 2009–10.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6); third term. Prerequisite: Ae/AM/CE/ME 102 abc or instructor's permission.* Theory of dislocations in crystalline media. Characteristics of dislocations and their influence on the mechanical behavior in various crystal structures. Application of dislocation theory to single and polycrystal plasticity. Theory of the inelastic behavior of materials with negligible time effects. Experimental background for metals and fundamental postulates for plastic stress-strain relations. Variational principles for incremental elastic-plastic problems, uniqueness. Upper and lower bound theorems of limit analysis and shakedown. Slip line theory and applications. Additional topics may include soils, creep and rate-sensitive effects in metals, the thermodynamics of plastic deformation, and experimental methods in plasticity. Not offered 2009–10.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* Subject matter will change from term to term depending upon staff and student interest but may include such topics as structural dynamics; aeroelasticity; thermal stress; mechanics of inelastic and composite materials; and nonlinear problems. Instructor: Staff.

Ae 228. Computational Mechanics Simulations Using Particles. *9 units (3-0-6); first term. Prerequisites: Ae/AM/CE/ME 214 or equivalent or Ae/ACM/ME 232 or equivalent, ACM 104, ACM 105, or equivalent.* Particle simulations of continuum and discrete systems. Advances in molecular, mesoscopic, and macroscale simulations using particles, identification of common computing paradigms and challenges across disciplines, discretizations and representations using particles, fast summation algorithms, time integrators, constraints, and multiresolution. Exercises will draw on problems simulated using particles from diverse areas such as fluid and solid mechanics, computer graphics, and nanotechnology. Instructor: Koumoutsakos.

Ae/ACM/ME 232 ab. Computational Fluid Dynamics. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; ACM 100 abc or equivalent.* Development and analysis of algorithms used in the solution of fluid mechanics problems. Numerical analysis of discretization schemes for partial differential equations including interpolation, integration, spatial discretization, systems of ordinary differential equations; stability, accuracy, aliasing, Gibbs and Runge phenomena, numerical dissipation and dispersion; boundary conditions. Survey of finite difference, finite element, finite volume and spectral approximations for the numerical solution of the incompressible and compressible Euler and Navier-Stokes equations, including shock-capturing methods. Not offered 2009–10.

Ae 233. Hydrodynamic Stability. *9 units (3-0-6); third term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* Laminar-stability theory as a guide to laminar-turbulent transition. Rayleigh equation, instability criteria, and response to small inviscid disturbances. Discussion of Kelvin-Helmholtz, Rayleigh-Taylor, Richtmyer-Meshkov, and other instabilities, for example, in geophysical flows. The Orr-Sommerfeld equation, the dual role of viscosity, and boundary-layer stability. Modern concepts such as pseudomomentum conservation laws and nonlinear stability theorems for 2-D and geophysical flows. Weakly nonlinear stability theory and phenomenological theories of turbulence. Not offered 2009–10.

Ae 234. Hypersonic Aerodynamics. *9 units (3-0-6); first term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent, AM 125 abc, or instructor's permission.* An advanced course dealing with aerodynamic problems of flight at hypersonic speeds. Topics are selected from hypersonic small-disturbance theory, blunt-body theory, boundary layers and shock waves in real gases, heat and mass transfer, testing facilities and experiment. Not offered 2009–10.

Ae 235. Rarefied Gasdynamics. *9 units (3-0-6); third term.* Molecular description of matter; distribution functions; discrete-velocity gases. Kinetic theory: free-path theory, internal degrees of freedom. Boltzmann equation: BBGKY hierarchy and closure, H theorem, Euler equations, Chapman-Enskog procedure, free-molecule flows. Collisionless and transitional flows. Direct simulation Monte Carlo methods. Applications. Not offered 2009–10.

Ae 237 ab. Nonsteady Gasdynamics. *9 units (3-0-6); first, second 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 2009–10.

Ae 239 ab. Turbulence. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM 101 abc.* 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. Subgrid-scale modeling. Turbulent mixing. Structure of low and high Reynolds number wall turbulence. Not offered 2009–10.

Ae 240. Special Topics in Fluid Mechanics. *Units to be arranged; first term.* Subject matter changes depending upon staff and student interest. Not offered 2009–10.

Ae 241. Special Topics in Experimental Fluid and Solid Mechanics. *9 units (3-0-6); second term. Prerequisites: Ae/APh 104 or equivalent or instructor's permission.* Energy from wind and sea. Not offered 2009–10.

Ae/BE 242. Biological Flows: Propulsion. *9 units (3-0-6); second term. Prerequisites: 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. Instructor: Dabiri.

BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6).* For course description, see Bioengineering.

Ae 244. Mechanics of Nanomaterials. *9 units (3-0-6); first 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 2009–10.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6); second, third terms. Prerequisite: Ae/AM/CE/ME 102 abc or Ae/Ge/ME 160 ab or instructor's permission.* Introduction to elastodynamics and waves in solids. Dynamic fracture theory, energy concepts, cohesive zone models. Friction laws, nucleation of frictional instabilities, dynamic rupture of frictional interfaces. Radiation from moving cracks. Thermal effects during dynamic fracture and faulting. Crack branching and faulting along nonplanar interfaces. Related dynamic phenomena, such as adiabatic shear localization. Applications to engineering phenomena and physics and mechanics of earthquakes. Not offered 2009–10.

ANTHROPOLOGY

An 22. Introduction to Sociocultural Anthropology. *9 units (3-0-6); first term.* Introduction to anthropological theory. Exploration of the diversity of human culture. Examination of the relationship between ecology, technology, and subsistence, patterns of marriage and residence, gender and sexual division of labor, reproduction, kinship, and descent. Links between economic complexity, population, social stratification, political organization, law, religion, ritual, and warfare are traced. Ethnic diversity and interethnic relations are surveyed. The course is oriented toward understanding the causes of cross-cultural variation and the evolution of culture. Instructor: Ensminger.

An 23. Human Evolution. *9 units (3-0-6); third term.* Introduction to human evolution, which is essential for understanding our species. Natural selection, sexual selection, genetics, systematics, behavioral ecology, and life history theory are covered. The order Primates is surveyed. Primary emphasis is on the hominid fossil and archeological record. Behavior, cognition, and culture of nonhuman primates and humans, as well as physical variation in present-day humans, is examined. Instructor: Campbell.

An 101. Selected Topics in Anthropology. *9 units (3-0-6); offered by announcement.* Instructor: Campbell.

An 135. Primate Behavior. *9 units (3-0-6); second term.* This course will examine how natural selection has shaped the social organization, life histories, reproductive strategies, social behavior, and cognitive abilities of nonhuman primates. It will review natural and sexual selection, examine the ecological and social pressures that shape primate behavior, and consider the role these principles play in shaping modern human behavior. Instructor: Frank.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Students in this class will help develop hypotheses, methods, and background information for the design of a new class to be offered in subsequent years, which will seek to pose and empirically test questions related to cultural and social aspects of the Caltech undergraduate experience. Central to this project will be an examination of the theory of social networks and the role they play in the academic and social experience. Other qualitative and quantitative methods for future data gathering will also be designed. Instructor: Ensminger.

An 150 ab. The Caltech Project. *9 units (3-0-6); second, third terms. Prerequisite: instructor's permission*. Hands-on immersion in a social scientific research project examining the Caltech undergraduate community. Core data collection will use social network analysis. As channels of information flow, social networks are key determinants of career success, moral values, learning, diffusion of innovations, voting, disease transmission, and even terrorism. Few topics have drawn the interest of such diverse disciplines as anthropology, sociology, political science, economics, mathematics, medicine, biology, computer science, and physics. What can this and other methods teach us about the Caltech community? Instructor: Ensminger.

APPLIED AND COMPUTATIONAL MATHEMATICS

ACM 10. Introduction to Applied and Computational Mathematics. *1 unit (1-0-0); first term.* This course will introduce the research areas of the ACM faculty through weekly overview talks by the faculty aimed at first-year undergraduates. This course should be a useful introduction to ACM for those interested in possibly majoring in the option. Graded pass/fail. Instructor: Schröder.

ACM 11. Introduction to Matlab and Mathematica. *6 units (2-2-2); first term. Prerequisites: Ma 1 abc, Ma 2 ab. 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: Gittens.

ACM 95/100 abc. Introductory Methods of Applied Mathematics. *12 units (4-0-8); first, second, third terms. Prerequisites: Ma 1 abc, Ma 2 ab (may be taken concurrently), or equivalents.* First term: complex analysis: analyticity, Laurent series, singularities, branch cuts, contour integration, residue calculus. Second term: ordinary differential equations. Linear initial value problems: Laplace transforms, series solutions. Linear boundary value problems: eigenvalue problems, Fourier series, Sturm-Liouville theory, eigenfunction expansions, the Fredholm alternative, Green's functions, nonlinear equations, stability theory, Lyapunov functions, numerical methods. Third term: linear partial differential equations: heat equation separation of variables, Fourier transforms, special functions, Green's functions, wave equation, Laplace equation, method of characteristics, numerical methods. Instructors: Pierce, Bruno.

ACM 101 abc. Methods of Applied Mathematics I. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc.* Analytical methods for the formulation and solution of initial and boundary value problems for ordinary and partial differential equations. Techniques include the use of complex variables, generalized eigenfunction expansions, transform methods and applied spectral theory, linear operators, nonlinear methods, asymptotic and approximate methods, Weiner-Hopf, and integral equations. Instructors: Guo, Hou.

ACM 104. Linear Algebra and Applied Operator Theory. *9 units (3-0-6); first term. Prerequisite: ACM 100 abc or instructor's permission.* Linear spaces, subspaces, spans of sets, linear independence, bases, dimensions; linear transformations and operators, examples, nullspace/kernel, range-space/image, one-to-one and onto, isomorphism and invertibility, rank-nullity theorem; products of linear transformations, left and right inverses, generalized inverses. Adjoints of linear transformations, singular-value decomposition and Moore-Penrose inverse; matrix representation of linear transformations between finite-dimensional linear spaces, determinants, multilinear forms; metric spaces: examples, limits and convergence of sequences, completeness, continuity, fixed-point (contraction) theorem, open and closed sets, closure; normed and Banach spaces, inner product and Hilbert spaces: examples, Cauchy-Schwarz inequality, orthogonal sets, Gram-Schmidt orthogonalization, projections onto subspaces, best approximations in subspaces by projection; bounded linear transformations, principle of superposition for infinite series, well-posed linear problems, norms of operators and matrices, convergence of sequences and series of operators; eigenvalues and eigenvectors of linear operators, including their properties for self-adjoint operators, spectral theorem for self-adjoint and normal operators; canonical representations of linear operators (finite-dimensional case), including diagonal and Jordan form, direct sums of (generalized) eigenspaces. Schur form; functions of linear operators, including exponential, using diagonal and Jordan forms, Cayley-Hamilton theorem. Taught concurrently with CDS 201. Instructor: Beck.

ACM 105. Applied Real and Functional Analysis. *9 units (3-0-6); second term. Prerequisite: ACM 100 abc or instructor's permission.* Lebesgue integral on the line, general measure and integration theory; Lebesgue integral in n-dimensions, convergence theorems, Fubini, Tonelli, and the transformation theorem; normed vector spaces, completeness, Banach spaces, Hilbert spaces; dual spaces, Hahn-Banach theorem, Riesz-Frechet theorem, weak convergence and weak solvability theory of boundary value problems; linear operators, existence of the adjoint. Self-adjoint operators, polar decomposition, positive operators, unitary operators; dense subspaces and approximation, the Baire, Banach-Steinhaus, open mapping and closed graph theorems with applications to differential and integral equations; spectral theory of compact operators; LP spaces, convolution; Fourier transform, Fourier series; Sobolev spaces with application to PDEs, the convolution theorem, Friedrich's mollifiers. Instructor: Shi.

ACM 106 abc. Introductory Methods of Computational Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ma 2 ab, ACM 11, ACM 95/100 abc 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 course covers methods such as direct and iterative solution of large linear systems; eigenvalue and vector computations; function minimization; nonlinear algebraic solvers; preconditioning; time-frequency transforms (Fourier, wavelet, etc.); root finding; data fitting; interpolation and approximation of functions; numerical quadrature; numerical integration of systems of ODEs (initial and boundary value problems); finite difference, element, and volume methods for PDEs; level set methods. Programming is a significant part of the course. Instructor: Yan.

ACM 113. Introduction to Optimization. *9 units (3-0-6); second term. Prerequisites: ACM 95/100 abc, ACM 11, 104 or equivalent, or instructor's permission.* Unconstrained optimization: optimality conditions, line search and trust region methods, properties of steepest descent, conjugate gradient, Newton and quasi-Newton methods. Linear programming: optimality conditions, the simplex method, primal-dual interior-point methods. Nonlinear programming: Lagrange multipliers, optimality conditions, logarithmic barrier methods, quadratic penalty methods, augmented Lagrangian methods. Integer programming: cutting plane methods, branch and bound methods, complexity theory, NP complete problems. Instructor: Owhadi.

ACM/CS 114. Parallel Algorithms for Scientific Applications. *9 units (3-0-6); second term. Prerequisites: ACM 11, 106 or equivalent.* Introduction to parallel program design for numerically intensive scientific applications. Parallel programming methods; distributed-memory model with message passing using the message passing interface; shared-memory model with threads using open MP, CUDA; object-based models using a problem-solving environment with parallel objects. Parallel numerical algorithms: numerical methods for linear algebraic systems, such as LU decomposition, QR method, CG solvers; parallel implementations of numerical methods for PDEs, including finite-difference, finite-element; particle-based simulations. Performance measurement, scaling and parallel efficiency, load balancing strategies. Instructor: Aivazis.

ACM/EE 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6); first term. Prerequisite: Ma 2 ab or instructor's permission.* Introduction to fundamental ideas and techniques of stochastic analysis and modeling. Random variables, expectation and conditional expectation, joint distributions, covariance, moment generating function, central limit theorem, weak and strong laws of large numbers, discrete time stochastic processes, stationarity, power spectral densities and the Wiener-Khinchine theorem, Gaussian processes, Poisson processes, Brownian motion. The course develops applications in selected areas such as signal processing (Wiener filter), information theory, genetics, queuing and waiting line theory, and finance. Instructor: Owhadi.

ACM/ESE 118. Methods in Applied Statistics and Data Analysis. *9 units (3-0-6); first term. Prerequisite: Ma 2 or another introductory course in probability and statistics.* Introduction to fundamental ideas and techniques of statistical modeling, with an emphasis on conceptual understanding and on the analysis of real data sets. Simple and multiple regression: estimation, inference, model checking. Analysis of variance, comparison of models, model selection. Principal component analysis. Linear discriminant analysis. Generalized linear models and logistic regression. Resampling methods and the bootstrap. Instructor: Tropp.

ACM 126 ab. Wavelets and Modern Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: ACM 11, 104, ACM 105 or undergraduate equivalent, or instructor's permission.* The aim is to cover the interactions existing between applied mathematics, namely applied and computational harmonic analysis, approximation theory, etc., and statistics and signal processing. The Fourier transform: the continuous Fourier transform, the discrete Fourier transform, FFT, time-frequency analysis, short-time Fourier transform. The wavelet transform: the continuous wavelet transform, discrete wavelet transforms, and orthogonal bases of wavelets. Statistical estimation. Denoising by linear filtering. Inverse problems. Approximation theory: linear/nonlinear approximation and applications to data compression. Wavelets and algorithms: fast wavelet transforms, wavelet packets, cosine packets, best orthogonal bases matching pursuit, basis pursuit. Data compression. Nonlinear estimation. Topics in stochastic processes. Topics in numerical analysis, e.g., multigrids and fast solvers. Not offered 2009–10.

Ma/ACM 142 abc. Ordinary and Partial Differential Equations. *9 units (3-0-6).* For course description, see Mathematics.

Ma/ACM 144 ab. Probability. *9 units (3-0-6)*. For course description, see Mathematics.

ACM 190. Reading and Independent Study. *Units by arrangement.* Graded pass/fail only.

ACM 201 ab. Partial Differential Equations. *12 units (4-0-8); second, third terms. Prerequisite: ACM 11, 101 abc or instructor's permission.* Fully nonlinear first-order PDEs, shocks, eikonal equations. Classification of second-order linear equations: elliptic, parabolic, hyperbolic. Well-posed problems. Laplace and Poisson equations; Gauss's theorem, Green's function. Existence and uniqueness theorems (Sobolev spaces methods, Perron's method). Applications to irrotational flow, elasticity, electrostatics, etc. Heat equation, existence and uniqueness theorems, Green's function, special solutions. Wave equation and vibrations. Huygens' principle. Spherical means. Retarded potentials. Water waves and various approximations, dispersion relations. Symmetric hyperbolic systems and waves. Maxwell equations, Helmholtz equation, Schrödinger equation. Radiation conditions. Gas dynamics. Riemann invariants. Shocks, Riemann problem. Local existence theory for general symmetric hyperbolic systems. Global existence and uniqueness for the inviscid Burgers' equation. Integral equations, single- and double-layer potentials. Fredholm theory. Navier-Stokes equations. Stokes flow, Reynolds number. Potential flow; connection with complex variables. Blasius formulae. Boundary layers. Subsonic, supersonic, and transonic flow. Not offered 2009–10.

ACM 210 ab. Numerical Methods for PDEs. *9 units (3-0-6); second, third terms. Prerequisite: ACM 11, 106 or instructor's permission.* Finite difference and finite volume methods for hyperbolic problems. Stability and error analysis of nonoscillatory numerical schemes: i) linear convection: Lax equivalence theorem, consistency, stability, convergence, truncation error, CFL condition, Fourier stability analysis, von Neumann condition, maximum principle, amplitude and phase errors, group velocity, modified equation analysis, Fourier and eigenvalue stability of systems, spectra and pseudospectra of nonnormal matrices, Kreiss matrix theorem, boundary condition analysis, group velocity and GKS normal mode analysis; ii) conservation laws: weak solutions, entropy conditions, Riemann problems, shocks, contacts, rarefactions, discrete conservation, Lax-Wendroff theorem, Godunov's method, Roe's linearization, TVD schemes, high-resolution schemes, flux and slope limiters, systems and multiple dimensions, characteristic boundary conditions; iii) adjoint equations: sensitivity analysis, boundary conditions, optimal shape design, error analysis. Interface problems, level set methods for multiphase flows, boundary integral methods, fast summation algorithms, stability issues. Spectral methods: Fourier spectral methods on infinite and periodic domains. Chebyshev spectral methods on finite domains. Spectral element methods and h-p refinement. Multiscale finite element methods for elliptic problems with multiscale coefficients. Instructor: Guo.

ACM 216. Markov Chains, Discrete Stochastic Processes and Applications. *9 units (3-0-6); second term. Prerequisite: ACM/EE 116 or equivalent.* Stable laws, Markov chains, classification of states, ergodicity, von Neumann ergodic theorem, mixing rate, stationary/equilibrium distributions and convergence of Markov chains, Markov chain Monte Carlo and its applications to scientific computing, Metropolis Hastings algorithm, coupling from the past, martingale theory and discrete time martingales, rare events, law of large deviations, Chernoff bounds. Instructor: Tropp.

ACM 217. Advanced Topics in Stochastic Analysis. *9 units (3-0-6); third term. Prerequisite: ACM 216 or equivalent.* The topic of this course changes from year to year and is expected to cover areas such as stochastic differential equations, stochastic control, statistical estimation and adaptive filtering, empirical processes and large deviation techniques, concentration inequalities and their applications. Examples of selected topics for stochastic differential equations include continuous time Brownian motion, Ito's calculus, Girsanov theorem, stopping times, and applications of these ideas to mathematical finance and stochastic control. Not offered 2009–10.

Ae/ACM/ME 232 ab. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ACM 256 ab. Special Topics in Applied Mathematics. *9 units (3-0-6); second, third terms. Prerequisite: ACM 101 or equivalent.* Introduction to finite element methods. Development of the most commonly used method—continuous, piecewise-linear finite elements on triangles for scalar elliptic partial differential equations; practical (a posteriori) error estimation techniques and adaptive improvement; formulation of finite element methods, with a few concrete examples of important equations that are not adequately treated by continuous, piecewise-linear finite elements, together with choices of finite elements that are appropriate for those problems. Homogenization and optimal design. Topics covered include periodic homogenization, G- and H-convergence, Gamma-convergence, G-closure problems, bounds on effective properties, and optimal composites. Not offered 2009–10.

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 2009–10.

ACM 270. Advanced Topics in Applied and Computational Mathematics. *Hours and units by arrangement.* Advanced topics in applied and computational mathematics that will vary according to student and instructor interest. May be repeated for credit. Instructor: Staff.

ACM 290 abc. Applied and Computational Mathematics Colloquium. *1 unit; first, second, third terms.* A seminar course in applied and computational mathematics. Weekly lectures on current developments are presented by staff members, graduate students, and visiting scientists and engineers. Graded pass/fail only.

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 abc. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

AM 125 abc. Engineering Mathematical Principles. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc.* Topics include linear spaces, operators and matrices, integral equations, variational principles, ordinary and partial differential equations, stability, perturbation theory. Applications to problems in engineering and science are stressed. Instructor: Beck.

AM/CE 151 ab. Dynamics and Vibration. *9 units (3-0-6); second, third terms.* Equilibrium concepts, conservative and dissipative systems, Lagrange's equations, differential equations of motion for discrete single and multi degree-of-freedom systems, natural frequencies and mode shapes of these systems (Eigen value problem associated with the governing equations), phase plane analysis of vibrating systems, forms of damping and energy dissipated in damped systems, response to simple force pulses, harmonic and earthquake excitation, response spectrum concepts, vibration isolation, seismic instruments, dynamics of continuous systems, Hamilton's principle, axial vibration of rods and membranes, transverse vibration of strings, beams (Bernoulli-Euler and Timoshenko beam theory), and plates, traveling and standing wave solutions to motion of continuous systems, Rayleigh quotient and the Rayleigh-Ritz method to approximate natural frequencies and mode shapes of discrete and continuous systems, frequency domain solutions to dynamical systems, stability criteria for dynamical systems, and introduction to nonlinear systems and random vibration theory. Instructor: Krishnan.

AM/ME 165 ab. Elasticity. *9 units (3-0-6); second, third terms. Prerequisites: Ae/Ge/ME 160 a and registered in Ae/Ge/ME 160 b.* Fundamental concepts and equations of elasticity. Linearized theory of elastostatics and elastodynamics: basic theorems and special solutions. Finite theory of elasticity: constitutive theory, semi-inverse methods. Variational methods. Applications to problems of current interest. Not offered 2009–10.

AM 200. Special Problems in Advanced Mechanics. *Hours and units by arrangement.* By arrangement with members of the staff, properly qualified graduate students are directed in independent studies in mechanics.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

AM 250. 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.

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5).* For course description, see Chemistry.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2); first, second terms; six units credit for the freshman laboratory requirement. Prerequisite: successful completion of APh/EE 9 a is a prerequisite for enrollment in APh/EE 9 b.* Introduction to solid-state electronics, including physical modeling and device fabrication. Topics: semiconductor crystal growth and device fabrication technology, carrier modeling, doping, generation and recombination, pn junction diodes, MOS capacitor and MOS transistor operation, and deviations from ideal behavior. Laboratory includes computer-aided layout, and fabrication and testing of light-emitting diodes, transistors, and inverters. Students learn photolithography, and use of vacuum systems, furnaces, and device-testing equipment. Instructor: Painter.

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. Instructors: Vahala, Crosignani.

APh 23. Demonstration Lectures in Optics. *6 units (2-0-4); second term. Prerequisite: Ph 1 abc.* This course cover fundamentals of optics with emphasis on modern optical applications, intended to exhibit basic optical phenomena including interference, dispersion, birefringence, diffraction, and laser oscillation, and the applications of these phenomena in optical systems employing two-beam and multiple-beam interferometry, Fourier-transform image processing, holography, electro-optic modulation, and optical detection and heterodyning. System examples to be selected from optical communications, radar, and adaptive optical systems. Instructor: Staff.

APh 24. Introductory Modern Optics Laboratory. *6 units (0-4-2); third term. Prerequisite: APh 23.* Laboratory experiments to acquaint students with the contemporary aspects of modern optical research and technology. Experiments encompass many of the topics and concepts covered in APh 23. Instructor: Staff.

APh 77 bc. Laboratory in Applied Physics. *9 units (0-9-0); second, third terms.* Selected experiments chosen to familiarize students with laboratory equipment, procedures, and characteristic phenomena in plasmas, fluid turbulence, fiber optics, X-ray diffraction, microwaves, high-temperature superconductivity, black-body radiation, holography, and computer interfacing of experiments. Instructor: Bellan.

APh 78 abc. Senior Thesis, Experimental. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research experience, open only to senior-class applied physics majors. Requirements will be set by individual faculty members, but will include a written report based upon actual laboratory experience. The selection of topic and the final report must be approved by the Applied Physics Undergraduate Committee. Students desiring additional units should register in APh 100. Not offered on a pass/fail basis. Instructor: Staff.

APh 79 abc. Senior Thesis, Theoretical. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research experience, open only to senior-class applied physics majors. Requirements will be set by individual faculty members, but will include a written report based upon actual laboratory experience. The selection of topic and the final report must be approved by the Applied Physics Undergraduate Committee. Not offered on a pass/fail basis. 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 105 abc. States of Matter. *9 units (3-0-6); first, second, third terms. Prerequisite: APh 17 abc or equivalent.* A survey emphasizing unifying concepts, such as order parameters, scaling laws, quasi-particle excitations, and correlation functions. Topics: long-range ordered states such as crystals, superfluids, and ferromagnets; phase transitions; critical phenomena; ideal classical and degenerate gases; theory of liquids; band theory of solids; fluctuations; noise. Part c taught concurrently with MS 105. Instructors: Johnson, Fultz.

APh 109. Introduction to the Micro/Nanofabrication Lab. *9 units (0-6-3); first, second, third terms.* Introduction to techniques of micro- and nanofabrication, including solid-state, optical, and microfluidic devices. Students will be trained to use fabrication and characterization equipment available in the applied physics micro- and nanofabrication lab. Topics include Schottky diodes, MOS capacitors, light-emitting diodes, microlenses, microfluidic valves and pumps, atomic force microscopy, scanning electron microscopy, and electron-beam writing. Instructor: 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: Schwab, Atwater.

APh/Ph 115 ab. Physics of Transport in Fluids. *9 units (3-0-6); first, second terms. Prerequisite: ACM 95 or equivalent.* There is growing interest in micro- and nanodevices consisting of small liquid structures or solid objects in contact with liquid media. These include oscillating cantilevers, microfluidic arrays, optofluidic devices, and biofluidic sensors, to name a few. This course will provide a self-contained treatment of the fundamentals of transport phenomena necessary for the development of such applications. Topics to include creeping and pulsatile flows, self-similar phenomena, lubrication and free surface flows, oscillating bubbles, spreading films, convective-diffusion processes, and instabilities leading to pattern formation. The first term will focus on fluid dynamical principles; the second term will examine processes triggered by thermal or concentration gradients. Instructor: Troian.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6); first term.* This course reviews EM theory and optical concepts that are frequently encountered. EM theory: tensor matrix, kDB space, Poynting theorem. Dispersion and absorption. Reflection at an interface. Nonlinear optics. Polarization: Jones matrix and Stokes vectors. Ray tracing: ABCD matrix, optical aberrations. Noise. Diffraction. Interferometry: system design, homodyne, heterodyne, spectral domain analysis. Instructor: Yariv.

EE/APh 131. Optical Wave Propagation. *9 units (3-0-6).* For course description, see Electrical Engineering.

APh/EE 132. Optoelectronic Materials and Devices. *9 units (3-0-6); third term.* Interaction of light and matter, spontaneous and stimulated emission, laser rate equations, mode-locking, Q-switching, semiconductor lasers. Optical detectors and amplifiers; noise characterization of optoelectronic devices. Propagation of light in crystals, electro-optic effects and their use in modulation of light; introduction to nonlinear optics. Optical properties of nanostructures. Instructor: Yariv.

APh 150. Topics in Applied Physics. *Units 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. Not offered 2009–10.

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 (magnetosphere, solar) will be discussed. Instructor: Bellan.

BE/APh 161. Physical Biology of the Cell. *9 units (3-0-6).* For course description, see Bioengineering.

BE/APh 162. Physical Biology Laboratory. *9 units (0-6-3).* For course description, see Bioengineering.

EE/APh 180. Solid-State Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6).* For course description, see Bioengineering.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6); third term.* Principles of semiconductor electronic structure, carrier transport properties, and optoelectronic properties relevant to semiconductor device physics. Fundamental performance aspects of basic and advanced semiconductor electronic and optoelectronic devices. Topics include energy band theory, carrier generation and recombination mechanisms, quasi-Fermi levels, carrier drift and diffusion transport, quantum transport. Instructor: Atwater.

APh 190 abc. Quantum Electronics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent.* Generation, manipulations, propagation, and applications of coherent radiation. The basic theory of the interaction of electromagnetic radiation with resonant atomic transitions. Laser oscillation, important laser media, Gaussian beam modes, the electro-optic effect, nonlinear-optics theory, second harmonic generation, parametric oscillation, stimulated Brillouin and Raman scattering. Other topics include light modulation, diffraction of light by sound, integrated optics, phase conjugate optics, and quantum noise theory. Not offered 2009–10.

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 abc. Advanced Condensed-Matter Physics. *9 units (3-0-6).* For course description, see Physics.

APh 250. Advanced Topics in Applied Physics. *Units and term to be arranged.* Content will vary from year to year; topics are chosen according to interests of students and staff. Visiting faculty may present portions of this course. Instructor: Staff.

APh 300. Thesis Research in Applied Physics. *Units in accordance with work accomplished.* APh 300 is elected in place of APh 200 when the student has progressed to the point where his or her research leads directly toward a thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

ART HISTORY

Art 11. Selected Topics in Art History. *9 units (3-0-6); offered by announcement.* Instructor: Staff.

Art 23. Major Figures in Art. *9 units (3-0-6); first term.* A course devoted to the study of a single artist of world importance, the name of the artist to be announced prior to registration. This study, grounded in the artist's life and, where possible, his/her writings, will analyze and interpret his/her major works in chronological sequence in their artistic and historic contexts, and attempt, by close aesthetic examination, to account for their greatness—and, sometimes, their failure. Not offered 2009–10.

Art 46. The Age of the Great Cathedrals. *9 units (3-0-6); third term.* A study of the arts of Western Europe from the disintegration of the Roman Empire circa A.D. 476, to the 14th century. The diverse historical forces at work during this long period produced a correspondingly varied art. Emphasis will be on the later Middle Ages, circa 1200–1350, a period marked by a synthesizing of inherited traditions into a comprehensive whole. Major monuments of architecture, such as the cathedrals of Notre Dame, Chartres, Reims, Cologne, Strasbourg, and Westminster, as well as sculpture, illuminated manuscripts, mosaics, panel painting, and stained glass will be examined within the aesthetic and social framework of countries as culturally diverse as France, Italy, Germany, Spain, and Britain. Not offered 2009–10.

Art 49. From Van Eyck to Rembrandt: Northern European Art, 1400–1650. *9 units (3-0-6); third term.* A survey of artistic developments in Northern Europe and Spain from the late Middle Ages through the Renaissance and baroque periods. The course will focus upon the complexity of northern art, from its origins in the still forceful medieval culture of 15th-century Flanders, to its confrontation with Italian Renaissance humanism in the 16th century. The effects of this cultural synthesis and the eventual development of distinct national schools of painting in the 17th century are examined through the works of the period's dominant artists, including Van Eyck, Dürer, Holbein, Velázquez, Rubens, Hals, and Rembrandt. Not offered 2009–10.

Art 50. Baroque Art. *9 units (3-0-6); first term.* A survey of the arts of painting, sculpture, and architecture from the late 16th century to the late 18th century. A confident and optimistic age, the baroque fostered the rise of national schools that produced artistic giants like Bernini, Caravaggio, Rubens, Rembrandt, Velázquez, Claude, Poussin, Tiepolo, and Guardi. The masterpieces of these and other artists reflect the wide variety of baroque art and will be studied within the context of certain commonly held ideals and of the differing economic, political, and religious systems that characterized the period. Not offered 2009–10.

Art 51. European Art of the 18th Century: From the Rococo to the Rise of Romanticism. *9 units (3-0-6); first term.* The course will encompass 18th-century European painting, sculpture, architecture, and the decorative arts. During this period a variety of styles and subjects proliferated in the arts, as seen in the richly diverse works of artists such as Watteau, Boucher, Chardin, Fragonard, Tiepolo, Canaletto, Hogarth, Gainsborough, Blake, David, Piranesi, and Goya, which reflect a new multiplicity in ways of apprehending the world. Not offered 2009–10.

Art 52. British Art. *9 units (3-0-6), third term.* A survey course on British painting, sculpture, and architecture in the 17th, 18th, and 19th centuries. By examining the works of well-known British artists such as Hogarth, Blake, Gainsborough, Reynolds, Constable, and Turner, the class will focus on the multiplicity of styles and themes that developed in the visual arts in Britain from 1740 to 1840 and are part of the wider artistic phenomenon known as romanticism. This introduction to the British visual arts will be enriched by several class meetings in the Huntington Art Gallery. Instructor: Bennett.

Art 55. Art of the 19th Century. *9 units (3-0-6); second term.* A survey of 19th-century art with an emphasis on French painting created between 1780 and 1880. The lectures will focus on issues such as the new image of the artist, the tension between public and private statements in the arts, the rise of landscape painting, the development of the avant-garde, and paintings of modern life during this period. Not offered 2009–10.

Art 66. Ancient Art: From the Pyramids to the Colosseum. *9 units (3-0-6); second term.* A survey of the art of the earliest civilization of the ancient near east and Mediterranean from the Bronze Age to A.D. 300. The major monuments—architectural, sculptural, and pictorial—of Mesopotamia, Egypt, the Aegean, Greece, and Rome will be examined as solutions to problems of form and function presented by communal political, economic, and religious life. Emphasis will be placed on the creation of Greco-Roman art, the foundation of the Western artistic tradition. Not offered 2009–10.

Art 67. Italian Renaissance Art. *9 units (3-0-6); first term.* A basic study of the greatest achievements of Italian painting, sculpture, and architecture in the 15th and 16th centuries. Masterpieces by a succession of artists such as Giotto, Masaccio, Brunelleschi, Donatello, Alberti, the Bellini, Leonardo da Vinci, Michelangelo, Raphael, Titian, Veronese, and others will be examined for their formal beauty and power, and studied as manifestations of individual genius in the context of their time and place: Italy, fragmented politically, yet at the peak of its cultural dominance. Not offered 2009–10.

Art 68. Modern Art. *9 units (3-0-6); third term.* An in-depth survey of international painting and sculpture of the first half of the 20th century. Crucial movements, among them fauvism, German expressionism, cubism, dadaism, surrealism, and American abstraction and realism between the two world wars, will be studied, and masterworks by a number of major artists of this period (e.g., Picasso, Matisse, Nolde, Duchamp, Magritte, Hopper) will be closely examined. Not offered 2009–10.

Art 70. Traditions of Japanese Art. *9 units (3-0-6), first term.* An introduction to the great traditions of Japanese art from prehistory through the Meiji Restoration (1868–1912). Students will examine major achievements of sculpture, painting, temple architecture, and ceramics as representations of each artistic tradition, whether native or adapted from foreign sources. Fundamental problems of style and form will be discussed, but aesthetic analysis will always take place within the conditions created by the culture. Instructor: Wolfgram.

Art 71. Arts of Buddhism. *9 units (3-0-6); offered by announcement.* 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. Not offered 2009–10.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6); first term.* This course examines interactions between art, science, and technological innovation in Europe and its colonies ca. 1500–1750. It will explore influential arguments that have linked the growth of empiricism in the sciences to naturalism in early modern visual art. Major topics may include the place of artistic training in scientific discovery, the "maker's knowledge" tradition, and relations of mind to body in early modern visual culture. Objects and images from local collections will be central to analysis. Instructor: Hunter.

Art 169. The Arts of Dynastic China. *9 units (3-0-6); second 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. Not offered 2009–10.

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 the Big Bang. There will be a series of laboratory exercises intended to highlight the path from data acquisition to scientific interpretation. Students will also be required to produce a term paper on an astronomical topic of their choice and make a short oral presentation. In addition, a field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Scoville.

Ge/Ay 11 c. Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 20. Basic Astronomy and the Galaxy. *10 units (3-1-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc.* The electromagnetic spectrum; ground and space observing techniques; spectroscopy: inferring the composition and physical properties of astronomical objects; stellar masses, distances, and motions; the birth, structure, evolution, and death of stars; the structure and dynamics of the Galaxy. Short labs will introduce optics, spectroscopy, and astronomical measurement techniques. Instructor: A. Sargent.

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); second term.* 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); second term.* Weekly seminar open to declared Ay majors at the discretion of the instructor; nonmajors who have taken astronomy courses may be admitted. Course is intended for sophomores and juniors. This seminar is held in faculty homes in the evening and is designed to encourage student communication skills as they are introduced to faculty members and their research. Each week a student will review a popular-level article in astronomy for the class. Graded pass/fail. Instructor: Readhead.

Ay 31. Writing in Astronomy. *3 units; 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 open only to those who have taken upper-level astronomy courses. *Fulfills the Institute scientific writing requirement.* Instructor: Hillenbrand.

Ay 40. Topics in Modern Astrophysics. *6 units (2-0-4); third term. Prerequisite: Ay 20. May be repeated for credit.* The course covers the process of star formation from both observational and theoretical perspectives. Topics include star-forming regions, physical processes in molecular clouds, core collapse and protostars, premain sequence stars, the impact of star formation upon environment, theoretical evolutionary models, primordial accretion disks, formation of planetary systems, circumstellar debris disks, star formation on galactic scales. Not offered 2009–10.

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.

Ay 78 abc. Senior Thesis. *9 units. Prerequisite: To register for this course, the student must obtain approval of the astronomy option representative and the prospective thesis adviser.* Open only to senior astronomy majors.

Research must be supervised by a faculty member. The written thesis must be completed and approved by the adviser before the end of the third term. Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the astronomy option representative. A grade will not be assigned in Ay 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.

Ay 101. Physics of Stars. *11 units (3-2-6); first term. Prerequisite: Ay 20 is recommended.* Physics of stellar interiors and atmospheres. Properties of stars, stellar spectra, radiative transfer, line formation. Stellar structure, stellar evolution. Nucleosynthesis in stars. Stellar oscillations. Instructor: W. Sargent.

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: Hirata.

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 consequenes: (neutron stars) pulsars, magnetars, X-ray binaries, gamma-ray bursts, gravity wave sources; (black holes) X-ray transients, quasars/active galaxies, and sources of low-frequency gravitatonal waves. Instructor: Phinney.

Ay 105. Optical Astronomy Instrumentation Lab. *9 units (1-6-2); third term. Prerequisite: Ay 20.* An opportunity for astronomy and physics undergraduates (juniors and seniors) to gain firsthand experience with the basic instrumentation tools of modern optical and infrared astronomy. The 10 weekly lab experiments are expected to include radiometry measurements, geometrical optics, optical aberrations and ray tracing, spectroscopy, fiber optics, CCD electronics, CCD characterization, photon counting detectors, vacuum and cryogenic technology, and stepper motors and encoders. Instructors: Hillenbrand, Martin.

Ay 111 ab. Introduction to Current Astrophysics Research. *3 units; second, third terms.* 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: J. Cohen.

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisites: Ph 125 or equivalent (undergraduates).* The interaction of radiation with matter: radiative transfer, emission, and absorption. Compton processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructor: Readhead.

Ay 122 abc. Astronomical Measurements and Instrumentation. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106 or equivalent.* Measurement and signal analysis techniques throughout the electromagnetic spectrum with focus (a) on infrared, optical, and ultraviolet techniques, (b) on radio through submillimeter techniques, and (c) on X-ray through gamma-ray techniques. Telescopes, optics, detectors, radiometers, photometry, spectroscopy. Active/adaptive optics. Interferometers/arrays. Imaging devices and image processing. Antennae, receivers, mixers, and amplifiers. Space telescopes. Probability and statistics as relevant to astronomical measurement. Some lab work and observatory field trips. In 2009–10 only parts a and b are offered. Instructors: Steidel, Kulkarni, Readhead.

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. Instructor: Ellis.

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. Instructors: Benson, Ellis.

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 106 or equivalent (undergraduates).* High-energy astrophysics and the final stages of stellar evolution; supernovae, binary stars, accretion disks, pulsars; extragalactic radio sources; active galactic nuclei; black holes. Instructor: Kulkarni.

Ay 126. Interstellar Medium. *9 units (3-0-6); second term. Prerequisite: Ay 102 (undergraduates).* Physical processes in the interstellar medium. Ionization, thermal and dynamic balance of interstellar medium, molecular clouds, hydrodynamics, magnetic fields, H II regions, supernova remnants, star formation, global structure of interstellar medium. Instructors: Phinney, W. Sargent.

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); third term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Cosmology; extragalactic distance determinations; relativistic cosmological models; galaxy formation and clustering; thermal history of the universe, microwave background; nucleosynthesis; cosmological tests. Instructors: Benson, Kamionkowski.

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. Instructor: Staff.

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. 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. Graded pass/fail.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6); second term.* Photochemistry of planetary atmospheres, comparative planetology, atmospheric evolution. What makes Earth habitable? Remote sensing of extrasolar planets, biosignatures. Instructor: Yung. Given in alternate years; not offered 2009–10.

Ay 199 ab. Special Topics in Astronomy and Astrophysics. *9 units (3-0-6); second, third terms.* Terms may be taken independently. Open to graduate and upper-division undergraduate students in all options. The topic for this year will be practical computational science methods that are useful in disciplines dealing with large and/or complex data sets.

The course will cover scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. This course is the same as Bi 199 ab. Not offered 2009–10.

Ay 211. Extragalactic Astronomy. *9 units (3-0-6); first term. Prerequisites: Ay 123, Ay 124, and Ay 127.* Contemporary 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. Instructors: Ellis, Hirata.

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term.* Course for graduate students and seniors in astronomy and planetary science. Students will be required to lead some discussions. Topic will be selected based on student interest. Instructor: Ott.

Ay 218. Extrasolar Planets and Stellar Seismology. *9 units (3-0-6); third term*. Close to 300 planets have been identified in orbit around normal stars. Astronomers are now embarking on understanding the statistics of extrasolar planet populations and characterizing with great precision individual planets, namely, determining their masses, radii, and in some cases, diagnosing their atmospheres. The successfully operating French mission COROT and the soon-to-be-launched NASA mission Kepler will dramatically increase the knowledge of extrasolar planets, primarily via their superb photometric precision. Such precision will also enable stellar seismology studies, as undertaken with the MOST satellite. These photometric missions will soon be followed by astrometric missions such as GAIA and SIM/PlanetQuest. The course will review the state of extrasolar planets, take up case studies, and anticipate findings. Not offered 2009–10.

Ay 219. Element Abundances from the Big Bang to the Present. *9 units (3-0-6); third 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 meteorites, stars, H II regions, and in interstellar and intergalactic gas using the electromagnetic spectrum from radio waves to X rays. Theory of nucleosynthesis in stars, supernovae and the Big Bang, including the s- and r-processes and explosive nucleosynthesis. Particular attention will be paid to the theory and observation of element synthesis in the "First Stars" in the universe. Emphasis will be placed on the connection between element synthesis, the initial mass function of star formation, and galactic evolution, including the role of galactic winds. Instructors: Cohen, Staff.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

BMB/Bi/Ch 170 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5); first, second, third terms. Prerequisite: Bi/Ch 110.* First term: 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. Energetic principles and molecular mechanism of enzymatic catalysis. Practical kinetic techniques. Second term: basic principles of modern biophysical and structural methods to interrogate macromolecules from the atomic to cellular levels, including X-ray crystallography, NMR spectroscopy, molecular dynamics, electron and light microscopy, AFM, single molecule techniques, and systems biological simulations. Third term: detailed analysis of specific macromolecular machines and systems that illustrate the principles and biophysical methods taught in the first two terms. Instructors: Clemons, Jensen, Shan, staff.

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 2009–10.

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. Graded pass/fail. Instructor: Pierce.

BE 98. Undergraduate Research in Bioengineering. *9 units (0-0-9)*. Undergraduate research with a written report at the end of each term; supervised by a Caltech faculty member, or coadvised by a Caltech faculty member and an external researcher. Graded pass/fail.

BE 100 abc. Bioengineering Seminar. *1 unit; first, second, third terms.* Required for first-year BE graduate students. Seminar series and training discussions with visiting speakers. Instructor: Asthagiri.

BE 103. Biomedical Diagnostics and Therapeutics. *6 units (3-0-3); first term.* Transformative ideas in biomedicine and bioengineering have their origins in disciplines ranging from materials science, chemistry, and biology to optics, computation, and mechanical engineering. This course will survey the inspiration and development of some of the most significant innovations that have impacted biomedical science. Diagnostics will include landmark contributions such as magnetic resonance imaging (MRI), polymerase chain reaction (PCR), and radio immune assay (RIA). Therapeutics will include pharmaceutical agents, organ transplantation, implantable devices, and microsurgery. Not offered 2009–10.

BE 104. Biomechanics Research Lab. *9 units (1-3-5); third term. Prerequisites: Ae/APh 104 ab.* Design, execution, and analysis of an original experiment related to biomechanics and/or bioinspired design. Instructor: Dabiri.

BE/Bi 105. Introduction to Biomechanics. *9 units (3-0-6); third term.* Introduction to the basic concepts of applying engineering principles of solid and fluid mechanics to the study of biological systems. The course emphasizes the organismal, rather than the molecular, level of complexity. It draws on a wide array of biological phenomena from plants and animals, and is not intended as a technical introduction to medically related biomechanics. Topics may include fundamental properties of solids and fluids, viscoelasticity, drag, biological pumps, locomotion, and muscle mechanics. Instructor: Dabiri.

BE 141. Biomaterials: Science and Engineering. *9 units (3-0-6); first term. Prerequisites: Ph 2 ab or Ph 12 abc, Ch 1 ab, Ch 3 a, or instructor's permission. MS 115 ab recommended.* Lectures and experiments demonstrating the bulk and surface properties of materials; review of the major classes of materials—metals, ceramics, polymers—with a view to their relevance to the biomedical field. Special materials and processes of relevance will also be discussed, e.g., hydrogels, fabrics, thin films, bioresorbable and bioerodible materials, cardiac jelly, etc. Proteins, cells, tissues and their interactions with materials; key concepts in reactions between host materials and implants, including inflammation, coagulation, and tumorigenesis. Testing and degradation of biomaterials, material applications in medicine and dentistry, especially orthopedic, cardiovascular, ophthalmologic, oral and maxillofacial implants, and artificial organs. Instructor: Ravi.

BE 142. Biomaterials: Mechanical Properties. *9 units (3-0-6); third term. Prerequisite: BE 141 recommended.* Mechanical characteristics of biological and related materials with a focus on the development of constitutive relationships in the context of elastic, plastic, and viscoelastic materials; cell mechanics; bioviscoelasticity with relevance to actin, elastin, collagen, and soft tissues; mechanical behavior of blood vessels; mechanics of muscles including skeletal and heart muscles; bone and cartilage. Experimental techniques for the measurement of biological forces will also be discussed. Not offered 2009–10.

BE 151. Elementary Molecular and Cellular Principles. *9 units (3-0-6); first term.* This course is designed for bioengineering students with a limited background in molecular biology and cell physiology. The course will describe the physiology of eukaryotic cells at the molecular, organelle, and cellular levels, emphasizing visualization and manipulation techniques. Instructor: Guo.

BE 152. The Physiology of Motion. *9 units (3-0-6); second term. Prerequisite: BE 151 or instructor's permission*. This course emphasizes physiological mechanisms related to biological motility that operate at tissue- and organism-levels of complexity. The central theme of the class is to examine biological motility across levels of biological organization, from the gating properties of ion channels to the biomechanics of running, swimming, and flying. Topics include excitable membranes, oscillatory circuits, sensory feedback, muscle mechanics, cardiovascular physiology, and the biomechanics of locomotion. Instructors: Fraser, Petrasek.

BE 153. Case Studies in Systems Physiology. *9 units (3-0-6); third term. Prerequisite: BE 151.* 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.

BE/APh 161. Physical Biology of the Cell. *9 units (3-0-6); second term.* 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.

BE/APh 162. Physical Biology Laboratory. *9 units (0-6-3); second term. Prerequisite: concurrent enrollment in BE/APh 161.* This laboratory course accompanies BE/APh 161 and is built around experiments that amplify material covered in that course. Particular topics include background on techniques from molecular biology, mechanics of lipid bilayer vesicles, DNA packing in viruses, fluorescence microscopy of cells, experiments on cell motility, and the construction of genetic networks. Instructor: Phillips.

ChE/BE 163. Introduction to Biomolecular Engineering. *9 units (3-0-6).* For course description, see Chemical Engineering.

EE/BE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5).* For course description, see Electrical Engineering.

BE 167. Topics in Bioengineering. *1 unit; first term. Required for first-year graduate BE students.* Introduction to the current research in bioengineering and related fields, focusing specifically on projects carried out by Caltech faculty. The course will provide the students with background within the lecturer's specific discipline. Instructor: Pierce.

ChE/BE 169. Biomolecular Cell Engineering. *9 units (3-0-6).* For course description, see Chemical Engineering.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6).* For course description, see Biology.

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6); third term. Prerequisites: APh 105, Ph129 or equivalent (students without a background in statistical physics are still encouraged to take the course—additional tutorial sessions will be arranged as needed).* Basic physics and chemical physics of interfaces between the fundamental realm of biology—molecules and cells—and the physical world. The course centers on processes that are essential for transduction to energy domains in which modern sensors operate. Information transfer from the biological realm to optical, electronic, and mechanical domains will be considered. Particular attention will be paid to both the sensitivity and the kinetics of transduction processes, and to how fluctuations affect and ultimately impose fundamental limits on such interactions. Instructor: Roukes.

EE/BE 185. MEMS Technology and Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

BE/EE 189. Design and Construction of Biodevices. *12 units (3-6-3); third term. Prerequisites: EE 45 and EE 111.* Students will design and construct devices for manipulating and studying biological systems. Topics covered: MEMS, circuit design, sensor/actuator-computer interface, optical sensing, microscopy. Possible design projects: microfluidic flow controls, blood fraction analysis system, antibody sensing platform, brine shrimp incubator. Instructor: Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6) second term; (2-4-3) third term. Prerequisites: ChE/BE 163. Recommended: CS 21, CS 129 ab, or equivalent.* This course investigates computation by molecular systems, emphasizing models of computation based on the underlying physics, chemistry, and organization of biological cells. We will explore programmability, complexity, simulation of and reasoning about abstract models of chemical reaction networks, molecular folding, molecular self-assembly, and molecular motors, with an emphasis on universal architectures for computation, control, and construction within molecular systems. If time permits, we will also discuss biological example systems such as signal transduction, genetic regulatory networks, and the cytoskeleton; physical limits of computation, reversibility, reliability, and the role of noise, DNA-based computers and DNA nanotechnology. Part a develops fundamental results; part b is a reading and research course: classic and current papers will be discussed, and students will do projects on current research topics. Instructor: Winfree.

BE 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.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4).* 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.

BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6); third 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. Instructor: Gharib.

BE/CNS 248. Magnetic Resonance Imaging. *9 units (3-1-5); first term. Prerequisites: Undergraduate-level physics, biology, and/or engineering courses recommended; basic quantum mechanics, statistics, and signal processing are helpful.* Physics, engineering, and computational aspects of MRI. Theory, engineering, and practice of MRI for biological and medical applications are covered in detail. Provides technical background necessary for a full understanding of the concepts underpinning the specific uses of MRI for functional brain imaging. Complements CNS/SS 251. Not offered 2009–10.

Bi/BE 250 c. Topics in Systems Biology. *9 units (3-0-6).* For course description, see Biology.

BE 251. Signal Transduction and Biomechanics in Eukaryotic Cell Morphogenesis. *6 units (3-0-3); third term. Prerequisite: BE 151 or instructor's permission.* This course describes the fundamental mechanisms governing eukaryotic cell morphogenesis, including embryonic pattern formation, cell polarization and migration in tissue development and regeneration, and synapse formation during immune responses. In addition to providing background material on cytoskeletal biomechanics and intra/intercellular signaling in cell-matrix and cell-cell interactions, the course will emphasize cell adhesion, epithelial planar cell polarity formation, the epithelial-mesenchymal transition, and spontaneous cell polarization and migration. The course will introduce appropriate tools and modeling techniques for analyzing pattern formation and collective behavior and will describe nano- and micro-fabrication approaches to the quantitative study of morphogensis. Instructor: Guo.

BE 262. Physical and Synthetic Biology Boot Camp. *9 units (1-8-0); summer.* This course provides an intensive research introduction to current projects in physical and synthetic biology. Projects are based on current research directions in participating labs, including those of visiting biologists invited for the course. Representative classes of experiments include quantitative fluorescent microscopy of cell and organelle dynamics, single-cell measurement of genetic expression levels during development, and design and construction of biological circuits in microbes. Graded pass/fail. Instructor: Phillips.

BIOLOGY

Bi 1. The Biology and Biophysics of Viruses. *9 units (4-0-5); third term.* This course introduces nonbiologists to recent advances in our understanding of how HIV and other viruses infect and cause damage to their hosts. Because understanding and treating HIV infection involves a basic knowledge of cell and molecular biology, virology, and immunology, the course will cover fundamental concepts in these areas from a quantitative, molecular, chemical, and biophysical perspective. Instructor: Bjorkman.

Bi 1 x. The Great Ideas of Biology: An Introduction 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: Phillips.

Bi 2. Current Research in Biology. *6 units (2-0-4); first term. Intended for students considering the biology option; open to freshmen.* Current research in biology will be discussed, on the basis of reading assigned in advance of the discussions, with members of the divisional faculty. Graded pass/fail. Instructor: Elowitz.

Bi 8. Introduction to Molecular Biology: Organization and Expression of Genetic Information. *9 units (3-0-6); second term.* This course and its sequel, Bi 9, cover biology at the cellular level. After introducing basic concepts necessary for understanding biological systems at the molecular level, Bi 8 emphasizes cellular processes involved in the organization and expression of genetic information, including what is commonly called molecular biology, and introduces topics in developmental biology and immunology. Instructor: Stathopoulos.

Bi 9. Cell Biology. *9 units (3-0-6); third term.* Continues coverage of biology at the cellular level, begun in Bi 8. Topics: cytoplasmic structure, membrane structure and function, cell motility, and cell-cell recognition. Emphasis on both the ultrastructural and biochemical approaches to these topics. Instructors: Rothenberg, staff.

Bi 10. Cell Biology Laboratory. *6 units (1-3-2); third term. Prerequisite: Bi 8; designed to be taken concurrently with Bi 9.* Introduction to basic methods in cell and molecular biological research, including polymerase chain reaction, molecular cloning, expression and purification of recombinant fusion proteins in bacteria, enzymology, and gel electrophoresis of proteins and nucleic acids. Instructor: Deshaies.

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 Tutorial. *Units to be arranged; usually 3, maximum of 6 units per term; second term.* Small group study and discussion in depth of special areas or problems in biology, involving regular tutorial sections with instructors. To be arranged with instructors before registration. Graded pass/fail. Instructor: Huang.

Bi 24. Technical Communication for Biologists. *6 units (2-0-4); first term.* This course offers instruction and practice in writing and speaking relevant to professional biologists working in research, teaching, and/or medical careers. Students may write a paper for a scientific journal, based on their previous research and mentored by a faculty member. Alternatively, students may produce a variety of brief writing assignments with a range of audiences and purposes. Oral presentations will be based on writing produced in the course, with feedback from instructors and peers. *Fulfills the Institute scientific writing requirement.* Instructors: Jensen, Youra, Marsen.

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: Lester.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph/Bi 103 b. Neuroscience for Physicists and Engineers. *9 units (3-0-6).* For course description, see Physics.

BE/Bi 105. Introduction to Biomechanics. *9 units (3-0-6).* For course description, see Bioengineering.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8); first term. Prerequisite: Ch 41 abc or instructor's permission.* Lectures and recitation introducing the molecular basis of life processes, with emphasis on the structure and function of proteins. Topics will include the derivation of protein structure from the information inherent in a genome, biological catalysis, the intermediary metabolism that provides energy to an organism, and the use of DNA manipulations, cloning, and expression of proteins in foreign hosts to study protein structure and function. Instructors: Richards, Campbell.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8); second term. Prerequisites: Bi/Ch 110; Bi 8 and Bi 122 recommended.* Lectures and recitation on the molecular basis of biological structure and function. Emphasizes the storage, transmission, and expression of genetic information in cells. Specific topics include DNA replication, recombination, repair and mutagenesis, transcription, RNA processing, and protein synthesis. Instructors: Campbell, Parker.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8); third term. Prerequisites: Bi/Ch 110; Bi 9 recommended.* Lectures and recitation on the biochemistry of basic cellular processes in the cytosol and at the cell surface, with emphasis on signal transduction, membrane trafficking, and control of cell division. Specific topics include cell-cell signaling, control of gene expression by cell surface molecules, tumorigenesis, endocytosis, exocytosis, viral entry, and cell cycle regulation. Instructors: Chan, Shan.

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, developmental regulation of gene rearrangement, biochemistry of lymphocyte activation, lymphokines and the regulation of cellular responses, T and B cell development, and mechanisms of tolerance. Instructor: Mazmanian.

Bi 115. Attack and Repulsion: Viruses and their Hosts. *6 units (2-0-4); spring term.* The course will introduce the chemistry and biology of viruses, emphasizing their diverse replication strategies. It will then focus on mechanisms used by viruses to multiply in the face of host defenses. It will also discuss cancer-inducing viruses. The course will mainly consider mammalian viruses but will also discuss aspects of plant and bacterial viruses. Instructor: Baltimore. Given in alternate years; offered 2009–10.

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-Fraser.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Bi 122. Genetics. *9 units (3-0-6); first term. Prerequisite: Bi 8 or Bi 9, or instructor's permission.* Lecture and discussion course covering basic principles of genetics. Instructor: Hay.

Bi 123. Genetics Laboratory. *12 units (2-8-2); second term. Prerequisite: Bi 122.* Laboratory exercises illustrating the principles of genetics, with emphasis on Mendelian inheritance in multicellular eukaryotes, including *Drosophila melanogaster* and *Caenorhabditis elegans*. Instructors: Hay, staff.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6); first term. Recommended prerequisite: Bi/Ch 110.* Structural and functional aspects of nucleic acids and proteins, including hybridization; electrophoretic behavior of nucleic acids; principles and energetics of folding of polypeptide chains in proteins; allostery and cooperativity in protein action; enzyme kinetics and mechanisms; and methods of structure determination, such as X-ray diffraction and magnetic resonance. Structure and function of metalloenzymes. Instructors: Beauchamp, Heath.

Bi/CNS/Psy 133. Neurobiology and Evolution of Emotion: Do Flies Have Feelings? *9 units (3-0-6); third term. Prerequisite: Bi/CNS 150 or instructor's permission. Recommended Bi 156 and SS/Psy/Bi/CNS 140.* Fundamental issues in emotion research at multiple levels of experimental analysis, and in species ranging from humans to mice to flies. Psychological theories and data from studies in humans will be presented to clarify the relationship between emotional behavior, affect, feelings, and moods, which in turn will form the basis for exploring whether and how different animal models can be used to investigate the neural circuit and molecular bases of emotion. Can genetically tractable model organisms such as flies show "emotional behavior," or have "feelings"? What have we learned from animal models about the neural circuit and genetic bases of emotional behavior, and how does it relate to what we know from human studies? Disorders of emotion will also be discussed, including affective disorders in humans, and their potential animal models. Instructors: Anderson, Adolphs.

SS/Psy/Bi/CNS 140. Social Neuroscience. *9 units (3-0-6).* For course description, see Social Science.

Bi 145 ab. Tissue and Organ Physiology. *9 units (4-0-5); first, second terms. Prerequisites: Bi 8, 9, 110, 117. Bi 110 may be taken concurrently.* Reviews of embryology, anatomy, and histology, as well as in-depth discussion of cellular physiology (from a control and digital logic perspective). Topics will include building from cell function to tissues, hematologic, connective tissue, musculoskeletal physiology, and integration of these tissue functions into the function of the cardiovascular system. Cardiovascular system in an organ-based fashion, with pulmonary, renal, gastrointestinal, hepatobiliary, neuroendocrine, and reproductive physiology. Specific topics in advanced physiology, including cardiovascular and pulmonary physiology, exercise, nutrition, congenital abnormalities, selected topics in pathophysiology. Instructors: Fraser, Pierce.

Bi 146. Human Anatomy. *9 units (4-0-5); second term. Prerequisites: Bi 8, Bi 9.* Introduction to human anatomy and histology. For biology majors interested in premed. May be taken concurrently with Bi 145. Topics include musculoskeletal, neural, cardiovascular, pulmonary, gastrointestinal, renal, endocrine and reproductive anatomy. Virtual labs required. Instructor: Tydell.

Bi/CNS 150. Introduction to Neuroscience. *10 units (4-0-6); first term. Prerequisites: Bi 8, 9, or instructors' permission.* General principles of the function and organization of nervous systems, providing both an overview of the subject and a foundation for advanced courses. Topics include the physical and chemical bases for action potentials, synaptic transmission, and sensory transduction; anatomy; development; sensory and motor pathways; memory and learning at the molecular, cellular, and systems level; and the neuroscience of brain diseases. Instructors: Adolphs, Kennedy, Lester.

Bi 152. Introduction to Neuroethology. *6 units (2-0-4); second term.* Introduction to the neurobiological study of natural behavior of animals. Topics include such questions as how animals recognize and localize signals in their natural environments, how animals move, how behavior develops, what and how animals learn, and how natural selection shapes the evolution of brain and behavior. Instructor: Konishi.

Bi 156. Molecular Basis of Behavior. *9 units (3-0-6); second term. Prerequisite: Bi 150 or instructor's permission.* A lecture and discussion course on the neurobiology of behavior. Topics may include biological clocks, eating behavior, sexual behavior, addiction, mental illness, and neurodegenerative diseases. Instructor: Patterson. Given in alternate years; offered 2009–10.

Bi/CNS 157. Comparative Nervous Systems. *9 units (2-3-4); third term.* 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. Instructor: Allman. Given in alternate years; not offered 2009–10.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6); third term.* 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. Instructor: Allman. Given in alternate years; offered 2009–10.

Bi/CNS 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3); third term. Prerequisite: Bi 150 or instructor's permission.* A laboratory-based introduction to experimental methods used for electrophysiological studies of the central nervous system. Through the term, students investigate the physiological response properties of neurons in insect and mammalian brains, using extra- and intracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, electrode fabrication, stimulus presentation, and computer-based data analysis. Graded pass/fail. Instructor: Wagenaar. Given in alternate years; offered 2009–10.

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 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5).* For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6); first 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, characteristics of lenses and microscopes, and principles of accurate imaging. 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. Emphasis in the second half of the course will be placed on the analysis and presentation of two- and three-dimensional images. No prior knowledge of microscopy will be assumed. Instructor: Fraser.

Bi 180. Methods in Molecular Genetics. *12 units (2-8-2); first term. Prerequisites: Bi 122, Bi 10, or instructor's permission.* An introduction to current molecular genetic techniques including basic microbiological procedures, transposon and UV mutagenesis, gene transfer, preparation of DNA, restriction, ligation, electrophoresis (including pulsed-field), electroporation, Southern blotting, PCR, gene cloning, sequencing, and computer searches for homologies. The first half of the course involves structured experiments designed to demonstrate the various techniques. The second half is devoted to individual research projects in which the techniques are applied to original studies on an interesting, but not well studied, organism. Graded pass/fail. Instructor: Bertani.

Bi 182. Developmental Gene Regulation and Evolution of Animals. *6 units (2-0-4); second term. Prerequisites: Bi 8 and at least one of the following: Bi 111, Bi 114, or Bi 122 (or equivalents).* Lectures on and discussion of the regulatory genome; phylogenetic relationships in animals and the fossil record; how developmental gene regulation works; regulatory basis of development in the simplest systems; making parts of the adult animal body plan; pattern formation and deep regulatory networks; the Precambrian world and a gene-regulatory view of the evolutionary origin of animal forms; processes of *cis*-regulatory evolution; diversification in the arthropods; and the special character of vertebrate evolution. Instructor: Davidson.

Bi/CNS 184. The Primate Visual System. *9 units (3-1-5); third term.* This class focuses on the primate visual system, investigating it from an experimental, psychophysical, and computational perspective. The course will focus on two essential problems: 3-D vision and object recognition. Topics include parallel processing pathways, functional specialization, prosopagnosia, object detection and identification, invariance, stereopsis, surface perception, scene perception, navigation, visual memory, multidimensional readout, signal detection theory, oscillations, and synchrony. It will examine how a visual stimulus is represented starting in the retina, and ending in the frontal lobe, with a special emphasis placed on mechanisms for high-level vision in the parietal and temporal lobes. The course will include a lab component in which students design and analyze their own fMRI experiment. Instructor: Tsao.

CNS/Bi/EE 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 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi 188. Human Genetics and Genomics. *6 units (2-0-4); third term. Prerequisite: Bi 122; or graduate standing and instructor's permission.* Introduction to the genetics of humans. Subjects covered include human genome structure, genetic diseases and predispositions, the human genome project, forensic use of human genetic markers, human variability, and human evolution. Given in alternate years; not offered 2009–10.

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. Advanced Genetics. *6 units (2-0-4); third term. Prerequisite: Bi 122.* Lectures and discussions covering advanced principles of genetic analysis. Emphasis on genetic approaches to the study of development in *Saccharomyces*, *Caenorhabditis*, *Drosophila*, and *Arabidopsis*. Instructor: Sternberg. Given in alternate years; not offered 2009–10.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi 199 ab. Special Topics in Computational Biology. *9 units (3-0-6); second, third terms.* Terms may be taken independently. Open to graduate and upper-division undergraduate students in all options. The topic for this year will be practical computational science methods that are useful in disciplines dealing with large and/or complex data sets. The course will cover scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. This course is the same as Ay 199 ab. Instructors: Djorgovski, Kennedy, CACR staff.

Bi 202. Neurobiology of Disease. *9 units (3-0-6); first term. Prerequisite: Bi 150 or instructor's permission.* This course will cover the cellular and molecular basis of diseases of the nervous system, as well as current and future therapeutic approaches. These diseases include disorders of abnormal protein structure (Alzheimer's, Huntington's, Parkinson's, prion), autoimmunity (multiple sclerosis), and developmental disorders of cognition and social communication (schizophrenia, autism). Genetic and environmental etiologies will be explored, and animal models will be compared to the human condition. The role of the reward system in addiction will also be discussed. Instructor: Patterson. Given in alternate years; not offered 2009–10.

Bi 204. Developmental Gene Regulatory Networks: Theory and Practice. *6 units (2-0-4); third term. Prerequisite: Bi 182 or equivalent, or instructor's permission.* A seminar about developmental gene regulatory networks (GRNs). It is specifically directed at the gene regulatory networks that control animal development as distinct from any prokaryote or yeast gene networks, or reversible physiological networks of complex organisms. Instructor: Davidson. Given in alternate years; not offered 2009–10.

Bi 206. Biochemical and Genetic Methods in Biological Research. *6 units (2-0-4); third term. Prerequisite: graduate standing or instructor's permission.* This course will comprise in-depth discussions of selected methods in molecular biology and related fields. Given the enormous range of techniques available to a molecular biologist nowadays, the course will focus on a subset of these methods that includes recent and highly promising techniques, with an emphasis on their robustness and general applicability. Instructor: Varshavsky.

Bi 214. Hematopoiesis: A Developmental System. *6 units (2-0-4); third term. Prerequisite: Bi 114, or Bi 182, or Bi 117 plus Bi/Ch 111, or graduate standing.* An advanced course with lectures and seminar presentations, based on reading from the current literature. The characteristics of blood cells offer unique insights into the molecular basis of lineage commitment and the mechanisms that control the production of diverse cell types from pluripotent precursors. The course will cover the nature of stem cells, the lineage relationships among differentiated cell types, the role of cytokines and cytokine receptors, apoptosis and lineage-specific proliferation, and how differentiation works at the level of gene regulation and regulatory networks. Roles of prominent regulatory molecules in hematopoietic development will be compared with their roles in other developmental systems. Emphasis will be on explanation of cellular and system-level phenomena in terms of molecular mechanisms. Instructor: Rothenberg. Given in alternate years; offered 2009–10.

Bi/CNS 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 2009–10.

Bi/CNS 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 2009–10.

Bi 218. Molecular Neurobiology Graduate Seminar. *6 units (2-0-4); second term.* Topics to be announced. Instructor: Anderson. Given in alternate years; not offered 2009–10.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Bi/CNS 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4); second term.* This advanced course will discuss the emerging science of neural "circuit breaking" through the application of molecular genetic tools. These include optogenetic and pharmacogenetic manipulations of neuronal activity, genetically based tracing of neuronal connectivity, and genetically based indicators of neuronal activity. Both viral and transgenic approaches will be covered, and examples will be drawn from both the invertebrate and vertebrate literature. Interested students who have little or no familiarity with molecular biology will be supplied with the necessary background information. Lectures and student presentations from the current literature. Instructor: Anderson. Given in alternate years; offered 2009–10.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4); first term. Prerequisite: instructor's permission.* 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. After introductory period, the course will consist of semi-independent weeklong modules organized around different imaging challenges. Early modules will focus on three-dimensional reconstruction of fixed cells and tissues, with particular attention being paid to accurately imaging very dim samples. Later modules will include time-lapse confocal analysis of living cells and embryos, including *Drosophila*, zebra fish, chicken, and *s* embryos. Dynamic analysis will emphasize the use of fluorescent proteins. No prior experience with confocal microscopy will be assumed; however, a basic working knowledge of microscopes is highly recommended. Preference is given to graduate students who will be using confocal microscopy in their research. Instructor: Fraser.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4).* For course description, see Chemistry.

Ge/Bi 244. Paleobiology Seminar. *6 units (3-0-3).* For course description, see Geological and Planetary Sciences.

Ge/Bi 246. Molecular Geobiology Seminar. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

CNS/Bi 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. Prerequisite: graduate standing.* Lectures and discussion covering research methods, logic, techniques and strategies, fundamental and general principles of modern biology, and unsolved problems. Students will learn to critique papers on molecular biology, cell biology, and genetics. Instructors: Deshaies, staff.

Bi/CNS 250 b. Topics in Systems Neuroscience. *9 units (3-0-6); second 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/BE 250 c. Topics in Systems Biology. *9 units (3-0-6); third term. Prerequisite: graduate standing.* The class will focus on quantitative studies of cellular and developmental systems in biology. It will examine the architecture of specific genetic circuits controlling microbial behaviors and multicellular development in model organisms. The course will approach most topics from both experimental and theoretical/computational perspectives. Specific topics include chemotaxis, multistability and differentiation, biological oscillations, stochastic effects in circuit operation, as well as higher-level circuit properties such as robustness. The course will also consider the organization of transcriptional and protein-protein interaction networks at the genomic scale. Instructor: Elowitz.

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 biology division labs. Undergraduate students require advance instructor's permission. Graded pass/fail. Instructors: Meyerowitz, Sternberg, staff.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi 256. Decision Making. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi 270. Special Topics in Biology. *Units to be arranged; first, second, third terms.* Students may register with permission of the responsible faculty member.

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged.* For course description, see Computation and Neural Systems.

Bi 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BUSINESS ECONOMICS AND MANAGEMENT

BEM/Ec/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4); second term.* This class provides the opportunity for students to improve their written and oral presentation skills in the social sciences. Students should come prepared with complete drafts of papers from another course or a SURF project, which they will substantially revise and improve in a style typical of peer-reviewed journals in their discipline. These papers must be the students' original work and must be papers with social science content. An initial introduction to the art of scientific writing will be provided by the staff of the Hixon Writing Center. In addition, each student will work closely with an HSS mentor whose own research is close to the student's paper topic. *Fulfills the Institute scientific writing requirement and the option oral presentation requirement for HSS majors.* Instructor: Yariv.

BEM 101. Introduction to Accounting. *9 units (3-0-6); first term.* An introduction to accounting in business. Topics include financial accounting, cost accounting. Instructor: Wang.

BEM 103. Introduction to Finance. *9 units (3-0-6); first term. Ec 11 recommended.* An introduction to corporate finance. Economic theory is used to study asset valuation and financial decision making in business. Topics include financial decision making under certainty, introduction to valuation of risky assets (stocks and bonds), the corporate investment decision, dividend policy, and the corporate financing decision. Instructor: Staff.

BEM 105. Options. *9 units (3-0-6). Prerequisites: BEM 103, some familiarity with statistics. Ec 11 recommended.* An introduction to modern option pricing theory. The focus is the valuation of contingent claims. Both American and European options are considered. The binomial and Black-Scholes option pricing models are derived. The theory is also applied to risky debt and portfolio choice. Instructor: Cvitanic.

BEM 106. Competitive Strategy. *9 units (3-0-6); third term. Prerequisite: Ec 11.* This course develops concepts appropriate for formulating strategy in a competitive environment, using a combination of case analysis and lectures. The course covers differentiation strategies, positioning to neutralize incumbency advantages, the product life cycle, organizational design as competitive strategy, signaling, cooperation strategies, pricing and price discrimination as competitive strategy, strategic use of option theory, and the war of attrition. Instructor: McAfee.

BEM 107. Advanced Corporate Finance: Governance, Transacting, and Valuation. *9 units (3-0-6); third term. Prerequisite: 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. Instructor: Cornell.

BEM 109. Fixed-Income and Credit-Risk Derivatives. *9 units (3-0-6); third term. Prerequisite: BEM 105.* An introduction to the models of interest rates and credit/default risk. The focus is on continuous time models used in Wall Street practice for pricing and hedging fixed income securities. Two main models for credit risk are considered: structural and reduced form. Not offered 2009–10.

BEM 110. Venture Capital. *9 units (3-0-6); first term. Prerequisites: BEM 101, 103.* An introduction to the theory and practice of venture capital and 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. Special attention is paid to the organization, funding, management, and growth of start-up companies. Instructor: Staff.

BEM 116. Advanced Business Strategy for Technology. *9 units (3-0-6); third term. Prerequisite: BEM 106.* This course develops tools to determine strategy for firms facing rapid technological change, great uncertainty, low marginal costs and high fixed costs of production, and short product life cycles. The focus is on firms with high levels of human capital (so-called high-tech firms). Special attention is paid to the product life cycle, patent strategy, pricing, and hiring and retention of talented individuals. Working in teams, students will be asked to formulate strategy in real business situations. Not offered 2009–10.

BEM/PS 126. Business and Public Policy. *9 units (3-0-6); first term. Prerequisite: PS 12 or equivalent*. This class studies the relationships among business, government, and interest groups as strategic actors in the nonmarket environment. Methods of influencing public policy are analyzed using the tools of modern political theory and ethical frameworks. Topics may include media, private collective action, international business, and corporate social responsibility. Knowledge of basic political and economic theory will be useful. Instructor: Snowberg.

BEM/Ec 146. Organization Design. *9 units (3-0-6). Prerequisite: Ec 11.* An introduction to the analysis, design, and management of organizations with an emphasis on incentives and information. Principles from economics, political science, and game theory will be applied to problems in project and team management, in organizational computing, and in allocating and pricing shared facilities. Instructor: Camerer.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6); first term. Prerequisite: PS/Ec 172.* The course covers issues of how firms are organized. Topics include the distribution of power and returns among shareholders, managers, and other stakeholders; the role of law, public policy, and financial markets in constraining or enabling firms to solve the problems they face; the interaction between history, financial market structure, and the ownership of very large firms. Instructor: Rosenthal.

BEM/Ec 186. Political Economy of Financial Markets. *9 units (3-0-6); third term. Prerequisite: BEM 103.* The course covers how the political process affects the structure of financial markets and how private actors influence financial regulation. Topics include government intervention in financial crises; how law, regulation, and financial markets affect the ownership and capital structure of firms; how elections and court decisions affect the value of stocks and bonds. Instructor: Rosenthal.

BEM 190. Undergraduate Research Project. *Units to be arranged; any term. Prerequisites: BEM 103, 106, and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research on a business problem individually or in small groups. Graded pass/fail.

CHEMICAL ENGINEERING

ChE 10. Introduction to Chemical Engineering. *3 units (2-0-1); second term; open to freshmen only.* 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 63 ab. Chemical Engineering Thermodynamics. *9 units (3-0-6); second, third terms.* A comprehensive treatment of classical thermodynamics with engineering and chemical applications and an introduction to statistical thermodynamics. First and second laws. Applications to closed and open systems. Equations of state. Thermochemical calculations. Properties of real fluids. Power generation and refrigeration cycles. Multicomponent systems, excess properties, fugacities, activity coefficients, and models of nonideal solutions. Chemical potential. Phase and chemical reaction equilibria. Introductory statistical thermodynamics. Instructors: Tirrell, Flagan.

ChE 64. Principles of Chemical Engineering. *9 units (3-0-6); first term.* Systems approach to conservation of mass and energy. Equilibrium staged separations. Instructor: Seinfeld.

ChE 80. Undergraduate Research. *Units by arrangement.* Research in chemical engineering offered as an elective in any term other than in the senior year. Graded pass/fail.

ChE 90 ab. Senior Thesis. *9 units (0-4-5); first, second, third terms.* A research project carried out under the direction of a chemical engineering faculty member. The project must contain a significant design component. Students must submit a proposal by the beginning of the first term of the thesis for review and approval. A grade will not be assigned prior to completion of the thesis, which normally takes two terms. A P grade will be given for the first term and then changed to the appropriate letter grade at the end of the course.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1).* For course description, see Chemistry.

ChE 101. Chemical Reaction Engineering. *9 units (3-0-6); second term. Prerequisites: ChE 63 ab and ChE 64.* Elements of chemical kinetics and chemically reacting systems. Homogeneous and heterogeneous catalysis. Chemical reactor analysis. Instructor: Arnold.

ChE 103 abc. Transport Phenomena. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc or concurrent registration*. 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, Davis.

ChE 105. Dynamics and Control of Chemical Systems. *9 units (3-0-6); third term. Prerequisites: ChE 101 or equivalent, ACM 95 abc or concurrent registration.* Analysis and design of dynamic chemical systems, spanning biomolecular networks to chemical processing. Topics include control strategies for regulating dynamic performance, formulation of mechanistic and empirical models, linear analysis of feedback systems, introduction to multivariate control. Instructor: Asthagiri.

ChE 110 ab. Optimal Design of Chemical Systems. *9 units (3-0-6); second, third terms. Prerequisites: ChE 63, ChE 101, ChE 103, or equivalents.* Introduction to process design; flow sheets for chemical processes; synthesis of multicomponent separation sequences and reaction paths; synthesis of heat exchange networks; optimization; process economics; simulation of chemical processes; design of a major process. Instructor: Vicic.

ChE 115. Electronic Materials Processing. *9 units (3-0-6); third term. Prerequisites: ChE 63 and ChE 103 or equivalent; ChE 101 or equivalent.* After a brief introduction to solid-state concepts, materials, and devices relevant to electronic applications, the course will cover the prevalent growth and etching techniques used in processing of electronic materials. Emphasis is on the underlying physical and chemical principles. Crystal and thin film growth techniques to be covered include physical and chemical vapor deposition, liquid-phase epitaxy, molecular beam epitaxy, and plasma-assisted deposition. Property altering processes such as diffusion, oxidation, and doping are also included. Plasma etching is introduced with emphasis on determining key parameters that control the ion energy and flux to the wafer surface. Key techniques for thin film analysis and characterization are briefly discussed. Instructor: Giapis. Given in alternate years; not offered 2009–10.

ChE 126. Chemical Engineering Laboratory. *9 units (1-6-2); first term. Prerequisites: ChE 63 ab, ChE 101, ChE 103, ChE 105, or equivalents.* 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, or equivalents.*Short-term, open-ended research projects targeting chemical processes in microreactors. Projects include synthesis of chemical products or materials, detection and destruction of environmental pollutants, and other gas phase conversions. Each student is required to construct and troubleshoot his/her own microreactor, then experimentally evaluate and optimize independently the research project using chemical engineering principles. Where possible, cost analysis of the optimized process is performed. Instructor: Vicic.

ChE 130. Biomolecular Engineering Laboratory. *9 units (1-5-3); third term. Prerequisites: ChE 63 ab, ChE 101 (concurrently) or instructor's permission.* Design, construction, and characterization of engineered biological systems that will be implemented in bacteria, yeast, and cell-free systems. Research problems will fall into the general areas of biomolecular engineering and synthetic biology. Emphasis will be on projects that apply rational and evolutionary design strategies toward engineering biological systems that exhibit dynamic, logical, or programmed behaviors. Instructors: Tirrell, Vicic.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6).* For course description, see Chemistry.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6).* For course description, see Chemistry.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6); third term. Prerequisite: Ch/ChE 147 or instructor's permission.* An introduction to the physics that govern polymer structure and dynamics in liquid and solid states, and to the physical basis of characterization methods used in polymer science. The course emphasizes the scaling aspects of the various physical properties. Topics include conformation of a single polymer chain under different solvent conditions; dilute and semi-dilute solutions; thermodynamics of polymer blends and block copolymers; rubber elasticity; polymer gels; linear viscoelasticity of polymer solutions and melts; glass transition and crystallization. Instructor: Wang. Given in alternate years; not offered 2009–10.

ChE 151 ab. Physical and Chemical Rate Processes. *12 units (3-0-9); first, second terms.* The foundations of heat, mass, and momentum transfer for single and multiphase fluids will be developed. Governing differential equations; laminar flow of incompressible fluids at low and high Reynolds numbers; forced and free convective heat and mass transfer, diffusion, and dispersion. Emphasis will be placed on physical understanding, scaling, and formulation and solution of boundary-value problems. Applied mathematical techniques will be developed and used throughout the course. Instructor: Brady.

ChE 152. Heterogeneous Kinetics and Reaction Engineering. *9 units (3-0-6); first term. Prerequisite: ChE 101 or equivalent.* Survey of heterogeneous reactions and reaction mechanisms on metal and oxide catalysts. Characterization of porous catalysts. Reaction, diffusion, and heat transfer in heterogeneous catalytic systems. Instructor: 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. Instructors: Davis, Labinger. Given in alternate years; offered 2009–10.

ChE/ESE 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. Instructor: Seinfeld.

ChE/BE 163. Introduction to Biomolecular Engineering. *9 units (3-0-6); third term. Prerequisites: Bi/Ch 110 or instructor's permission.* The course introduces rational design and evolutionary methods for engineering functional protein and nucleic acid systems. Rational design topics include molecular modeling, positive and negative design paradigms, simulation and optimization of equilibrium and kinetic properties, design of catalysts, sensors, motors, and circuits. Evolutionary design topics include evolutionary mechanisms and tradeoffs, fitness landscapes, directed evolution of proteins, and metabolic pathways.

Some assignments require programming (MATLAB or Python). Instructors: Arnold, Pierce.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6); second term. Prerequisite: Ch 21 abc or equivalent.* An introduction to the fundamentals and simple applications of statistical thermodynamics. Foundation of statistical mechanics; partition functions for various ensembles and their connection to thermodynamics; fluctuations; noninteracting quantum and classical gases; heat capacity of solids; adsorption; phase transitions and order parameters; linear response theory; structure of classical fluids; computer simulation methods. Instructors: Wang, Miller.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6); first term. Prerequisite: ChE 63 ab or equivalent.* 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/BE 169. Biomolecular Cell Engineering. *9 units (3-0-6); first term. Prerequisites: ChE 101 or Ch 24 ab or equivalent, ACM 95 b or concurrent registration.* Quantitative analysis of molecular mechanisms governing mammalian cell behavior. Topics include topology and dynamics of signaling and genetic regulatory networks, receptor-ligand trafficking, and biophysical models for cell adhesion and migration. Instructor: Asthagiri.

ChE 174. Special Topics in Transport Phenomena. *9 units (3-0-6); third term. Prerequisites: ACM 95/100, ChE 151 ab. May be repeated for credit.* Advanced problems in heat, mass, and momentum transfer. Introduction to mechanics of complex fluids; physicochemical hydrodynamics; microstructured fluids; colloidal dispersions; microfluidics; selected topics in hydrodynamic stability theory; transport phenomena in materials processing. Other topics may be discussed depending on class needs and interests. Instructor: Brady.

ChE 280. Chemical Engineering Research. *Offered to Ph.D. candidates in chemical engineering.* Main lines of research now in progress are covered in detail in section two.

CHEMISTRY

Ch 1 ab. General Chemistry. *6 units (3-0-3) first term; 9 units (4-0-5) second term.* Lectures and recitations dealing with the principles of chemistry. First term: electronic structure of atoms, periodic properties, ionic substances, covalent bonding, Lewis representations of molecules and ions, shapes of molecules, Lewis acids and bases, Bronsted acids and bases, hybridization and resonance, bonding in solids. Second term: chemical equilibria, oxidation and reduction, thermodynamics, kinetics, introduction to organic chemistry and the chemistry of life. Graded pass/fail. Instructors: Lewis, Heath, Reisman.

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5); third term. Prerequisites: Ch 1 ab, Ph 1 ab, Ma 1 ab.* Energy production and transduction in biological, chemical, and nuclear reactions. Bioenergetics: energy sources and storage; components of biological energy flows: pumps, motors, and solar cells; circuitry of biological energy flows and biological energy transduction pathways. Chemistry of energy production and utilization: fossil fuel utilization and energy conversion pathways; artificial photosynthesis, solar cells, and solar energy conversion. Principles of nuclear energy production: nuclear energy decay processes, fission and fusion reactions, and reactor principles. Not offered on a pass/fail basis. Instructors: Lewis, Bellan. *Satisfies the menu requirement of the Caltech core curriculum.*

Ch 3 a. Fundamental Techniques of Experimental Chemistry. *6 units (1-3-2); first, second, third terms.* Introduces the basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. Freshmen who have gained advanced placement into Ch 41 or Ch 21, or who are enrolled in Ch 10, are encouraged to take Ch 3 a in the fall term. Graded pass/fail. Instructor: Staff.

Ch 3 b. Experimental Procedures of Synthetic Chemistry. *8 units (1-6-1); first, third terms. Prerequisites: Ch 1 ab and Ch 3 a.* Instruction in fundamental synthesis, separation, and characterization procedures used in chemical research. Enrollment in the spring term is limited, with priority given to chemical engineering majors. Instructor: Staff.

Ch 3 x. Fundamental Techniques of Experimental Chemistry. *6 units (1-4-1); second, third terms.* Concepts and laboratory methods in general chemistry are introduced with application to materials. This course will beta test a new suite of experiments for Ch 3 a and will satisfy the freshman chemistry laboratory course requirement. A lecture component is included. Limited enrollment. Instructors: Winkler, Brunschwig.

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.* 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 emphasizes spectroscopic methods of analysis; Ch 4 b stresses applications of chromatography in addition to more classical separation techniques. Ch 4 a, second term; Ch 4 b, third term only. Instructor: Staff.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. *Ch 5 a 12 units (1-9-2), second term; Ch 5 b 9 units (1-6-2), first term. Prerequisite: Ch 4 ab. Ch 102 strongly recommended for Ch 5 b.* Modern synthetic chemistry. Specific experiments may change from year to year. Experiments illustrating the multistep syntheses of natural products (Ch 5 a), coordination complexes, and organometallic complexes (Ch 5 b) will be included. Methodology will include advanced techniques of synthesis and instrumental characterization. Terms may be taken independently. Instructors: Grubbs (a), Bercaw (b).

Ch 6 ab. Physical and Biophysical Chemistry Laboratory. *10 units (1-6-3); second, third terms. Prerequisites: Ch 1, Ch 4 ab, and Ch 21 or Ch 24 or equivalents (may be taken concurrently).* Introduction to modern physical methods in chemistry and biology. Techniques include laser spectroscopy, microwave spectroscopy, electron spin resonance, nuclear magnetic resonance, mass spectrometry, FT-IR, fluorescence, X-ray diffraction, scanning probe microscopies, and UHV surface methods. The two terms can be taken in any order. Instructors: Beauchamp, Weitekamp.

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 the powerful contemporary methods for polypeptide and oligonucleotide synthesis. Experiments will address nucleic acid and amino acid protecting group strategies, biopolymer assembly and isolation, and product characterization. A strong emphasis will be placed on understanding the chemical basis underlying the successful utilization of these procedures. In addition, experiments to demonstrate the application of commercially available enzymes for useful synthetic organic transformations will be illustrated. Instructor: Hsieh-Wilson.

Ch 10 abc. Frontiers in Chemistry. *3 units (2-0-1); first, second terms. 8 units (1-6-1); third term. Open for credit to freshmen and sophomores. Prerequisites: Ch 10 c prerequisites are Ch 10 ab, Ch 3 a, and either Ch 1 ab, Ch 41 ab, or Ch 21 ab, and instructor's permission.* Ch 10 ab is a weekly seminar by a member of the chemistry department on a topic of current research; the topic will be presented at an informal, introductory level. The other weekly session will acquaint students with the laboratory techniques and instrumentation used on the research topics. Ch 10 c is a research-oriented laboratory course, which will be supervised by a chemistry faculty member. Weekly class meetings will provide a forum for participants to discuss their research projects. Graded pass/fail. Instructors: Hsieh-Wilson, Dervan.

Ch 14. Chemical Equilibrium and Analysis. *6 units (2-0-4); third term.* A systematic treatment of ionic equilibria in solution. Topics covered include acid-base equilibria in aqueous and nonaqueous solutions, complex ion formation, chelation, oxidation-reduction reactions, and some aspects of reaction mechanisms. Instructors: Richards, Shahgholi.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); first term. Prerequisites: Ch 1 ab, Ch 3 a, 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.

Ch 21 abc. Physical Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 ab, Ph 2 ab, Ma 2 ab.* Atomic and molecular quantum mechanics, spectroscopy, thermodynamics, statistical mechanics, and chemical kinetics. Instructors: McKoy, Okumura, Miller.

Ch 24 ab. Introduction to Biophysical Chemistry. *9 units (3-0-6); second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc, Ch 21 a or Ph 2 ab (may be taken concurrently).* Fundamental physical chemistry, with emphasis on those topics most important in biology. Molecular spectroscopy and statistical mechanics with applications to biological polymers, solution thermodynamics, transport processes, and reaction kinetics. Instructors: Rees, S. Chan.

Ch 41 abc. Organic Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ch 1 ab or instructor's permission.* The synthesis, structures, and mechanisms of reactions of organic compounds. Instructors: Dervan, Stoltz.

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. Prerequisite: 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, a thesis of approximately 20 pages (excluding figures and references) will be presented to the mentor and the Chemistry Curriculum and Undergraduate Studies Committee. An oral thesis defense will be arranged by the CUSC. The thesis must be approved by both the research mentor and the CUSC. The first two terms of Ch 82 will be taken on a pass/fail basis, and the third term will carry a letter grade. Instructor: Rees.

Ch 90. Oral Presentation. *3 units (2-0-1); second term.* Training in the techniques of oral presentation of chemical and biochemical topics. Practice in the effective organization and delivery of technical reports before groups. Graded pass/fail. Instructors: Zewail, Bikle.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1); third term.* Training in the writing of scientific research papers for chemists and chemical engineers. *Fulfills the Institute scientific writing requirement.* Instructor: Labinger.

Ch 102. Introduction to Inorganic Chemistry. *9 units (3-0-6); third term. Prerequisite: Ch 41 ab.* Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, and biological inorganic chemistry. Letter grades only. Instructor: Agapie.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8).* For course description, see Biology.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8).* For course description, see Biology.

Ch 112. Inorganic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 102 or instructor's permission.* Introduction to group theory, ligand field theory, and bonding in coordination complexes and organo-transition metal compounds. Systematics of synthesis, bonding, and reactivities of commonly encountered classes of transition metal compounds. Instructor: Bercaw.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8).* For course description, see Biology.

Ch 117. Introduction to Electrochemistry. *6 units (2-0-4); second term.* Discussion of the structure of electrode-electrolyte interface, the mechanism by which charge is transferred across it, and experimental techniques used to study electrode reactions. Topics change from year to year but usually include diffusion currents, polarography, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Not offered 2009–10.

Ch 120 ab. Nature of the Chemical Bond. *9 units (3-0-6) second, (1-1-7) third terms. 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) third term; Ch 121 b (1-1-7) first term. Prereq-*

uisites: Ch 21 a or Ch 125 a. Atomistic-based methods for predicting the structures and properties of molecules and solids and simulating the dynamical properties. The course will highlight theoretical foundations and applications of atomistic simulations to current problems in such areas as biological systems (proteins, DNA, carbohydrates, lipids); polymers (crystals, amorphous systems, copolymers); semiconductors (group IV, III-V, surfaces, defects); inorganic systems (ceramics, zeolites, superconductors, and metals); organometallics, and catalysis (heterogeneous and homogeneous). Part a covers the basic methods with hands-on applications to systems of interest using modern software. All homework and exams emphasize computer-based solutions. Part b: each student selects a research project and uses atomistic simulations to solve it. Instructor: Goddard. Part b not offered 2009–10.

Ch 122. Structure Determination by X-ray Crystallography. *9 units (3-0-6); first term. Prerequisites: Ch 21 abc or instructor's permission.* Methods for solving the crystal structures of organic and inorganic molecules, peptides, nucleic acids, and proteins. Topics include symmetry, space groups, diffraction by crystals, the direct and reciprocal lattice, powder diffraction, Patterson and direct methods for phase determination, isomorphous replacement phasing for macromolecules, and structure refinement. Instructor: Day.

Ch 125 abc. The Elements of Quantum Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ch 21 abc or an equivalent brief introduction to quantum mechanics.* A first course in molecular quantum mechanics consisting of a quantitative treatment of quantum mechanics with applications to systems of interest to chemists. The basic elements of quantum mechanics, the electronic structure of atoms and molecules, the interactions of radiation fields and matter, scattering theory, and reaction rate theory. Instructors: Kuppermann, McKoy.

Ch 126. Molecular Spectra and Molecular Structure. *9 units (3-0-6); third term. Prerequisite: Ch 21 and Ch 125 a taken concurrently, or instructor's permission.* Quantum mechanical foundations of the spectroscopy of molecules. Topics include quantum theory of angular momentum, rovibrational Hamiltonian for polyatomic molecules, molecular symmetry and permutation-inversion groups, electronic spectroscopy, interaction of radiation and matter. Not offered 2009–10.

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).* For course description, see Geological and Planetary Sciences.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6).* For course description, see Biology.

Ch 135 ab. Chemical Dynamics. *9 units (3-0-6); part a, second term; part b, third term. Prerequisites: Ch 21 abc and Ch 41 abc, or equivalent, or* *instructor's permission.* Part a: introduction to the dynamics of chemical reactions. Topics include scattering cross sections, rate constants, intermolecular potentials, reactive scattering, nonadiabatic processes, statistical theories of unimolecular reactions, and the application of laser and molecular beam techniques to the study of reaction mechanisms. Part b: the quantum description of chemical reactions. The scattering matrix. The calculation of reaction cross sections, probabilities, and rate constants. Collision lifetimes and resonances. Classical trajectories. The two terms can be taken independently. Instructors: Marcus, Okumura. Part b not offered 2009–10.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6); second, third terms. Prerequisite: APh/EE 9 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. Not offered 2009–10.

Ch 143. Basic FT NMR Spectroscopy. *9 units (3-2-4); second term. Prerequisite: Ch 41 abc.* The course will cover NMR basics and applications, with emphasis on FT NMR and the principles of multipulse NMR techniques used in structural analysis, including determination of relaxation times, INEPT, DEPT, NOSEY, and COSY. A number of NMR techniques will be illustrated with the Chapman-Russell *FT NMR Problems* videodisc-based computer program, which features on-screen spectra at a variety of magnetic fields with, and without, decoupling, 2-D spectra, and so on. The practical use of NMR will be further demonstrated by laboratory exercises using modern pulse FT NMR techniques with high-field spectrometers for structural analysis. Instructors: Roberts, Virgil.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); first, second terms. Prerequisite: Ch 41 abc; Ch 21 abc recommended.* An advanced survey of selected topics in modern physical organic chemistry. Topics vary from year to year and may include structural and theoretical organic chemistry; molecular recognition/supramolecular chemistry; reaction mechanisms and the tools to study them; reactive intermediates; materials chemistry; pericyclic reactions; and photochemistry. Instructor: Dougherty. Part b not offered 2009–10.

Ch 145. Bioorganic Chemistry of Proteins. *9 units (3-0-6); second term. Prerequisite: Ch 41 abc; Bi/Ch 110 recommended.* An advanced survey of current and classic topics in bioorganic chemistry/chemical biology. The content will vary from year to year and may include the structure, function, and synthesis of peptides and proteins; enzyme catalysis and inhibition; carbohydrates and glycobiology; chemical genetics; genomics and proteomics; posttranslational modifications; chemical tools to study cellular dynamics; and enzyme evolution. Instructor: Hsieh-Wilson.

Ch 146. Bioorganic Chemistry of Nucleic Acids. *9 units (3-0-6); third term. 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). Given in alternate years; not offered 2009–10.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 41 abc.* An introduction to the chemistry of polymers, including synthetic methods, mechanisms and kinetics of macromolecule formation, and characterization techniques. Instructor: Grubbs.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 153. Advanced Inorganic Chemistry. *9 units (2-0-7); second term. Prerequisites: Ch 112 and Ch 21 abc or concurrent registration.* Topics in modern inorganic chemistry. Electronic structure, spectroscopy, and photochemistry with emphasis on examples from the modern research literature. Instructors: Gray, Winkler.

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: Labinger. Part b not offered 2009–10.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 166. Nonequilibrium Statistical Mechanics. *9 units (3-0-6); third term. Prerequisite: Ch 21 abc or equivalent.* Transport processes in dilute gases; Boltzmann equation; Brownian motion; Langevin and Fokker-Planck equations; linear response theory; time-correlation functions and applications; nonequilibrium thermodynamics. Instructor: Marcus.

BMB/Bi/Ch 170 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5).* 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.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ch 180. Chemical Research. *Units by arrangement. Offered to M.S. candidates in chemistry.* Graded pass/fail.

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. Instructor: Agapie, Winkler.

Ch 213 abc. Advanced Ligand Field Theory. *12 units (1-0-11); first, second, third terms. Prerequisite: Ch 21 abc or concurrent registration.* A tutorial course of problem solving in the more advanced aspects of ligand field theory. Recommended only for students interested in detailed theoretical work in the inorganic field. Instructors: Gray, staff.

Ch 224. Advanced Topics in Magnetic Resonance. *9 units (2-0-7); third term. Prerequisite: Ch 125 abc or Ph 125 abc or concurrent registration or equivalent; Ch 122 b or equivalent.* A detailed presentation of some of the important concepts in magnetic resonance unified by the spin density operator formalism. Topics will include both classic phenomena and recent development, especially in solid-state and two-dimensional NMR. Instructor: Weitekamp.

Ch 227 ab. Advanced Topics in Chemical Physics. *9 units (3-0-6); part a second term; part b third term. Prerequisite: Ch 125 abc or Ph 125 abc or equivalent.* The general quantum mechanical theory of molecular collisions will be presented in detail. Quasi-classical, semi-classical, and other approximations. Applications to inelastic and reactive molecule-molecule and inelastic electron-molecule collisions. Instructor: Heath. Not offered 2009–10.

Ch 228. Dynamics and Complexity in Physical and Life Sciences. *9 units (3-0-6); third term.* This course is concerned with the dynamics of molecular systems, with particular focus on complexity, the elementary motions that lead to functions in chemical and biological assemblies. It will address principles of dynamics as they relate to the nature of the chemical bond. An overview of modern techniques, such as those involving lasers, NMR, and diffraction, for unraveling dynamics in complex systems. Applications from areas of physics, chemistry, and biology—from coherence and chaos to molecular recognition and self-assembly. Instructor: Zewail.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4); third term.* Transcriptional regulation in eukaryotes. Topics: the subunit structure of eukaryotic RNA polymerases and their role in transcriptional reactions; the composition of eukaryotic promoters, including regulatory units; general and specific transcription factors; developmental regulatory circuits and factors; structural motifs involved in DNA binding and transcriptional initiation and control. Instructors: Parker, Campbell.

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: Reisman, Virgil, Stoltz.

Ch 247. Organic Reaction Mechanisms. *6 units (2-0-4); third term.* A mechanistic view of free-radical reactions using examples from biological systems. Topics: initiation, termination, and propagation of radical reactions in vivo, mechanisms of lipid damage, spin labeling, photosynthesis, oxygen radicals and oxygen toxicity, and radical reactions in proteins and nucleic acids. Not offered 2009–10.

Ch 250. Advanced Topics in Chemistry. *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. Instructors: Grubbs, Stoltz.

Ch 280. Chemical Research. *Hours and units by arrangement.* By arrangement with members of the faculty, properly qualified graduate students are directed in research in chemistry.

CIVIL ENGINEERING

CE 90 abc. Structural 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 2009–10.

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 abc. Computational Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: instructor's permission.* Numerical analysis by the finite element method covering fundamental concepts and computer implementation. Solution of systems of linear equations and eigenvalue problems. Solution of the partial differential equations of heat transfer, solid and structural mechanics, and fluid mechanics. Transient and nonlinear problems. Not offered 2009–10.

CE 130 abc. Civil Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in civil engineering are required to attend a graduate seminar, in any division, each week of each term. Students not registered for the M.S. degree in civil engineering must receive the instructor's permission. Graded pass/fail. Instructor: Staff.

AM/CE 151 ab. Dynamics and Vibrations. *9 units (3-0-6).* For course description, see Applied Mechanics.

CE 160 ab. Structural and Earthquake Engineering. *9 units (3-0-6); second, third terms.* Matrix structural analysis of the static and dynamic response of structural systems, Newmark time integration, Newton-Raphson iteration methodology for the response of nonlinear systems, stability of iteration schemes, static and dynamic numerical analysis of planar beam structures (topics include the development of stiffness, mass, and damping matrices, material and geometric nonlinearity effects, formulation of a nonlinear 2-D beam element, uniform and nonuniform earthquake loading, soil-structure interaction, 3-D beam element formulation, shear deformations, and panel zone deformations in steel frames, and large deformation analysis), seismic design and analysis of steel moment frame and braced frame systems, steel member behavior (topics include bending, buckling, torsion, warping, and lateral torsional buckling, and the effects of residual stresses), reinforced concrete member behavior (topics include bending, shear, torsion, and PMM interaction), and seismic design requirements for reinforced concrete structures. Not offered 2009–10.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5).* For course description, see Aerospace.

CE 180. Experimental Methods in Earthquake Engineering. *9 units (1-5-3); third term. Prerequisite: AM/CE 151 abc or equivalent.* Laboratory work involving calibration and performance of basic transducers suitable for the measurement of strong earthquake ground motion, and of structural response to such motion. Study of principal methods of dynamic tests of structures, including generation of forces and measurement of structural response. Not offered 2009–10.

CE 181 ab. Engineering Seismology. *9 units (3-0-6); second, third terms.* Characteristics of potentially destructive earthquakes from the engineering point of view. Theory of seismometers, seismic waves in a continuum, plane waves in layered media, surface waves, basin waves, site effects, dynamic deformation of buildings, seismic sources, earthquake size scaling, earthquake hazard calculations, rupture dynamics. Instructor: Heaton.

CE 200. Advanced Work in Civil Engineering. *6 or more units as arranged; any term.* Members of the staff will arrange special courses on advanced topics in civil engineering for properly qualified graduate students. The following numbers may be used to indicate a particular area of study.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/CE 221. Space Structures. *9 units (3-0-6).* For course description, see Aerospace.

CE 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: Koch.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6); second, third terms. Prerequisites: Bi/CNS 150 and CNS/Bi/Ph/CS 187, or instructor's permission.* Introduction to the computations made by the brain during economic and social decision making and their neural substrates. First quarter: Signal detection theory. Unconscious and conscious processing. Emotion and the somatic marker hypothesis. Perceptual decision making. Reinforcement learning. Goal and habit learning. Facial processing in social neuroscience. Second quarter: Optimal Bayesian decision making and prospect theory. Standard and behavioral game theory. Evolution and group decision making. Collective decision making by animals. Instructors: Adolphs, Camerer, Koch, Rangel.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5-0-3.5).* This course covers tools and statistical methods used in cognitive neuroscience research. Topics vary from year to year depending on the interests of the students. Recent topics include statistical modeling for fMRI data, experimental design for fMRI, and the preprocessing of fMRI data. Instructor: Rangel.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5); third term.* What are the correlates of consciousness in the brain? The course provides a framework for beginning to address this question using a reductionist point of view. It focuses on the neurophysiology of the primate visual system, but also discusses alternative approaches more suitable for work with rodents. Topics to be covered include the anatomy and physiology of the primate's visual system (striate and extrastriate cortical areas, dorsal/ventral distinction, visual-frontal connections), iconic and working memory, selective visual attention, visual illusions, clinical studies (neglect, blind sight, split-brain, agnosia), direct stimulation of the brain, delay and trace associative conditioning, conscious and unconscious olfactory processing, and philosophical approaches to consciousness. Instructor: Koch.

Psy/CNS 130. Introduction to Human Memory. *9 units (3-0-6).* For course description, see Psychology.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6); second term.* This course will serve as an introduction to basic concepts, findings, and theory from the field of behavioral psychology, covering areas such as principles of classical conditioning, blocking and conditioned inhibition, models of classical conditioning, instrumental conditioning, reinforcement schedules, punishment and avoidance learning. The course will track the development of ideas from the beginnings of behavioral psychology in the early 20th century to contemporary learning theory. Not offered 2009–10.

Bi/CNS/Psy 133. Neurobiology and Evolution of Emotion: Do Flies Have Feelings? *9 units (3-0-6).* For course description, see Biology.

SS/Psy/Bi/CNS 140. Social Neuroscience. *9 units (3-0-6).* For course description, see Social Science.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6).* For course description, see Electrical Engineering.

Bi/CNS 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

Bi/CNS 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 159. Projects in Machine Learning and AI. *9 units (0-0-9).* For course description, see Computer Science.

Bi/CNS 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3).* For course description, see Biology.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3).* For course description, see Computer Science.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6); third term.* The cornerstone of current progress in understanding the mind, the brain, and the relationship between the two is the study of human and animal cognition. This course will provide an in-depth survey and analysis of behavioral observations, theoretical accounts, computational models, patient data, electrophysiological studies, and brain-imaging results on mental capacities such as attention, memory, emotion, object representation, language, and cognitive development. Instructor: Shimojo.

CNS 180. Research in Computation and Neural Systems. *Units by arrangement with faculty. Offered to precandidacy students.*

Bi/CNS 184. The Primate Visual System. *9 units (3-1-5).* For course description, see Biology.

CNS/Bi/EE 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: Perona, Shimojo, Koch. Given in alternate years; offered 2009–10.

CNS/Bi/Ph/CS 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.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6); second term. Prerequisite: Ma 2 or IST 4.* Advanced topics related to computational methods in biology. Topics might change from year to year. Examples include spectral analysis techniques and their applications in threshold circuits complexity and in computational learning theory. The role of feedback in computation. The logic of computation in gene regulation networks. The class includes a project that has the goal of learning how to understand, criticize, and present the ideas and results in research papers. Instructor: Bruck.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi/CNS 216. Behavior of Mammals. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS 217. Central Mechanisms in Perception. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4).* For course description, see Biology.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5); third term. Prerequisite: Bi/CNS 150 or instructor's permission.* Lecture and discussion aimed at understanding computational aspects of information processing within the nervous system. The course will emphasize single neurons and how their biophysical properties relate to neuronal coding, i.e., how information is actually represented in the brain at the level of action potentials. Topics include biophysics of single neurons, signal detection and signal reconstruction, information theory, population coding and temporal coding in sensory systems of invertebrates and in the primate cortex. Students are required to hand in three homework assignments, discuss one set of papers in class, and participate in the debates. Not offered 2009–10.

CNS/Bi 247. Cerebral Cortex. *6 units (2-0-4); second term. Prerequisite: Bi/CNS 150 or equivalent.* A general survey of the structure and function of the cerebral cortex. Topics include cortical anatomy, functional localization, and newer computational approaches to understanding cortical processing operations. Motor cortex, sensory cortex (visual, auditory, and somatosensory cortex), association cortex, and limbic cortex. Emphasis is on using animal models to understand human cortical function and includes correlations between animal studies and human neuropsychological and functional imaging literature. Instructor: Andersen. Given in alternate years; not offered 2009–10.

BE/CNS 248. Magnetic Resonance Imaging. *9 units (3-1-5).* For course description, see Bioengineering.

Bi/CNS 250 b. Topics in Systems Neuroscience. *9 units (3-0-6).* For course description, see Biology.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (3-1-5); 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). Not offered 2009–10.

CNS/SS 252. Experimental Design and Research Methods in Cognitive Neuroscience. *9 units (3-0-6); second term.* This course will cover the basics of experimental design, research methods, and statistics for use in cognitive neuroscience. It will cover different types of experimental designs commonly used in cognitive neuroscience, including factorial designs, parametric designs, randomized block designs, nested designs, repeated measure designs; the statistics required to analyze such data, including t-tests, linear and multiple regression analyses, analysis of variance, random and fixed effects, all under the rubric of the general linear model, and model-free or "non-parametric" statistics. Undergraduate students may register with instructor's permission. Not offered 2009–10.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3).* For course description, see Computer Science.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi 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.*

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged. First, second, third terms.* Students may register with permission of the responsible faculty member.

COMPUTER SCIENCE

CS 1. Introduction to Computer Programming. *9 units (3-4-2); first term.* A course on computer programming emphasizing the program design process and pragmatic programming skills. It will use the Python programming language and will not assume previous programming experience. Material covered will include data types, variables, assignment, control structures, functions, scoping, compound data, string processing, modules, basic input/output (terminal and file), as well as more advanced topics such as recursion, exception handling and object-oriented programming. Program development and maintenance skills including debugging, testing, and documentation will also be taught. Assignments will include problems drawn from fields such as graphics, numerics, networking, and games. At the end of the course, students will be ready to learn other programming languages in courses such as CS 11, and will also be ready to take more in-depth courses such as CS 2 and CS 4. Instructor: Vanier.

CS 2. Introduction to Programming Methods. *9 units (2-4-3); second term. Prerequisite: CS 1 or equivalent.* CS 2 is a challenging course in programming languages and computer science, emphasizing modes of algorithmic expression. The course will include such topics as performance analysis of algorithms; proofs of program correctness; recursive and higher-order procedures; data structures, including lists, trees, graphs, and arrays; objects and abstract data types. The course includes weekly laboratory exercises and written homework covering the lecture material and program design. Instructor: Barr.

CS 3. Introduction to Software Engineering. *9 units (2-4-3); third term. Prerequisite: CS 2 or equivalent.* CS 3 is an advanced introduction to the fundamentals of computer science and software engineering methodology. Topics will be chosen from the following: abstract data types; object-oriented models and methods; logic, specification, and program composition; abstract models of computation; probabilistic algorithms; nondeterminism; distributed algorithms and data structures. The weekly laboratory exercises allow the students to investigate the lecture material by writing nontrivial applications. Instructor: Staff.

CS 4. Fundamentals of Computer Programming. *9 units (3-4-2); second term. Prerequisite: CS 1 or instructor's permission.* This course gives students the conceptual background necessary to construct and analyze programs, which includes specifying computations, understanding evaluation models, and using major programming language constructs (functions and procedures, conditionals, recursion and looping, scoping and environments, compound data, side effects, higher-order functions and functional programming, and object-oriented programming). It emphasizes key issues that arise in programming and in computation in general, including time and space complexity, choice of data representation, and abstraction management. This course is intended for students with some programming background who want a deeper understanding of the conceptual issues involved in computer programming. Instructor: Vanier.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6).* For course description, see Mathematics.

CS 9. Introduction to Computer Science Research. *1 unit (1-0-0); first term.* This course will introduce the research areas of the computer science faculty, through weekly overview talks by the faculty aimed at first-year undergraduates. Others may wish to take the course to gain an understanding of the scope of the field. Graded pass/fail. Instructor: Umans.

CS 11. Computer Language Shop. *3 units (0-3-0); first, second, third terms. Prerequisite: CS 1 or instructor's permission.* A self-paced lab that provides students with extra practice and supervision in transferring their programming skills to a particular programming language; the course can be used for any language of the student's choosing, subject to approval by the instructor. A series of exercises guide the student through the pragmatic use of the chosen language, building his or her familiarity, experience, and style. More advanced students may propose their own programming project as the target demonstration of their new language skills. CS 11 may be repeated for credit of up to a total of nine units. Instructors: Vanier, Pinkston.

CS 21. Decidability and Tractability. *9 units (3-0-6); second term. Prerequisite: CS 2 (may be taken concurrently).* This course introduces the formal foundations of computer science, the fundamental limits of computation, and the limits of efficient computation. Topics will include automata and Turing machines, decidability and undecidability, reductions between computational problems, and the theory of NP-completeness. Instructor: Umans.

CS 24. Introduction to Computing Systems. *9 units (3-3-3); third term. Prerequisites: CS 2; and CS 21 or CS/EE/Ma 129 a.* Basic introduction to computer systems, including hardware-software interface, computer architecture, and operating systems. Course emphasizes computer system abstractions and the hardware and software techniques necessary to support them, including virtualization (e.g., memory, processing, communication), dynamic resource management, and common-case optimization, isolation, and naming. Instructor: Pinkston.

CS 38. Introduction to Algorithms. *9 units (3-0-6); third term. Prerequisites: CS 2; Ma/CS 6 a or Ma 121 a; and CS 21 or CS/EE/Ma 129 a.* This course introduces techniques for the design and analysis of efficient algorithms. Major design techniques (the greedy approach, divide and conquer, dynamic programming, linear programming) will be introduced through a variety of algebraic, graph, and optimization problems. Methods for identifying intractability (via NP-completeness) will be discussed. Instructor: Schulman.

CS 42. Introduction to Relational Databases. *9 units (3-0-6); second term. Prerequisite: CS 1 or equivalent.* Introduction to the basic theory and usage of relational database systems. It covers the relational data model, relational algebra, and the Structured Query Language (SQL). The course introduces the basics of database schema design and covers the entity-relationship model, functional dependency analysis, and normal forms. Additional topics include other query languages based on the relational calculi, data-warehousing and dimensional analysis, writing and using stored procedures, working with hierarchies and graphs within relational databases, and an overview of transaction processing and query evaluation. Extensive hands-on work with SQL databases. Instructor: Pinkston.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3).* For course description, see Electrical Engineering.

EE/CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0).* For course description, see Electrical Engineering.

EE/CS 53. Microprocessor Project Laboratory. *12 units (0-12-0).* For course description, see Electrical Engineering.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or up to 18 units (2-15-1), with instructor's permission, third term.* This course presents the fundamentals of modern multidisciplinary systems engineering in the context of a substantial design project. Students from a variety of disciplines will conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components. Specific tools will be provided for setting project goals and objectives, managing interfaces between component subsystems, working in design teams, and tracking progress against tasks. Students will be expected to apply knowledge from other courses at Caltech in designing and implementing specific subsystems. During the first two terms of the course, students will attend project meetings and learn some basic tools for project design, while taking courses in CS, EE, and ME that are related to the course project. During the third term, the entire team will build, document, and demonstrate the course design project, which will differ from year to year. Freshmen must receive permission from the lead instructor to enroll. Not offered 2009–10.

CS 80 abc. Undergraduate Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained sufficiently early to allow time for planning the research.* Individual research project, carried out under the supervision of a member of the computer science faculty (or other faculty as approved by the computer science undergraduate option representative). Projects must include significant design effort. Written report required. Open only to upperclass students. Not offered on a pass/fail basis. Instructor: Staff.

CS 81 abc. Undergraduate Laboratory in Computer Science. *Units in accordance with work accomplished. Consent of both research adviser and course supervisor required before registering.* Supervised experimental research in computer science by undergraduates. Topic must be approved by the supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: Staff.

CS 90. Undergraduate Research in Computer Science. *Units in accordance with work accomplished. Consent of both research adviser and course supervisor required before registering.* Supervised research in computer science by undergraduates. Topic must be approved by the supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: Staff.

CS 101 abc. Special Topics in Computer Science. *Units in accordance with work accomplished; offered by announcement. Prerequisites: CS 21 and CS 38, or instructor's permission.* The topics covered vary from year to year, depending on the students and staff. Primarily for undergraduates.

CS 102 abc. Seminar in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

CS 103 abc. Reading in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

ACM/CS 114. Parallel Algorithms for Scientific Applications. *9 units.* For course description, see Applied and Computational Mathematics.

CS 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. Not offered 2009–10.

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. Instructor: Holzmann.

CS 119. Reliable Software: Testing and Monitoring. *9 units (3-3-3); third term. Prerequisites: CS 1 or equivalent; CS 116 and CS 118 are recommended.* The class discusses theoretical and practical aspects of software testing and monitoring. Topics include finite state machine testing algorithms, random testing, constraint-based testing, coverage measures, automated debugging, logics and algorithms for runtime monitoring, and aspect-oriented approaches to monitoring. Emphasis is placed on automation. Students will be expected to develop and use software testing and monitoring tools to develop reliable software systems. Not offered 2009–10.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6), first and second terms; (1-4-4) third term. Prerequisite: basic knowledge of probability and discrete mathematics.* A basic course in information theory and computational complexity with emphasis on fundamental concepts and tools that equip the student for research and provide a foundation for pattern recognition and learning theory. *First term:* what information is and what computation is; entropy, source coding, Turing machines, uncomputability. *Second term:* topics in information and complexity; Kolmogorov complexity, channel coding, circuit complexity, NP-completeness. *Third term:* theoretical and experimental projects on current research topics. Instructor: Winfree.

ME/CS 132. Advanced Robotics: Navigation and Vision. *9 units (3-6-0).* For course description, see Mechanical Engineering.

CS 138 abc. Computer Algorithms. *9 units (3-0-6); first, second, third terms. Prerequisites: CS 21 and CS 38, or instructor's permission.* Design and analysis of algorithms. Techniques for problems concerning graphs, flows, number theory, string matching, data compression, geometry, linear algebra and coding theory. Optimization, including linear programming. Randomization. Basic complexity theory and cryptography. Not offered 2009–10.

CS 139 abc. Concurrency in Computation. *9 units (3-0-6); first, second, third terms. Prerequisites: CS 21 and CS 38, or instructor's permission.* Design and verification of concurrent algorithms. Topics: different models of concurrent computations; process synchronization by shared variables and synchronization primitives; distributed processes communicating by message exchange; the concepts of synchronization, indivisible actions, deadlock, and fairness; semantics and correctness proofs; implementation issues; and application to VLSI algorithm design. Parallel machine architecture issues include mapping a parallel algorithm on a network of processors, and classical parallel algorithms and their complexity. Not offered 2009–10.

CS 141 abc. Distributed Computation Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisites: CS 3, CS 21 and CS 38, or instructor's permission.* This laboratory course deals with the systematic design and implementation of high-confidence scalable networks of communicating objects that discover other objects, configure themselves into collaborating groups of objects, and adapt to their environment. Teams of students explore theories and methods of implementation to obtain predictability and adaptability in distributed systems. Each team of students is expected to submit a research paper at the end of the third term, schedule demonstrations periodically, and maintain documents describing their project status. Instructor: Chandy. Given in alternate years; offered 2009–10.

CS/EE 143. Communication Networks. *9 units (3-3-3); first term. Prerequisite: Ma 2 ab.* This course introduces the basic mechanisms and protocols in communication networks, and mathematical models for their analysis. It covers topics such as digitization, switching, switch design, routing, error control (ARQ), congestion control, layering, queuing models, optimization models, basics of protocols in the Internet, wireless networks, and optical networks. This course can be combined with CS/EE 144 and CS/EE 145 to satisfy the project requirement for CS undergraduate degree. Instructor: Low.

CS/EE 144. Ideas behind the Web. *9 units (3-0-6); second term. Prerequisite: Ma 2 ab.* The Web is an essential part of our lives, and we all depend on it every day, but do you really know what makes it work? This course studies the "big" ideas behind the Web: How do search engines work? How can search engines make so much money from putting ads next to their search results? Are there ways to prevent spammers from accumulating lots of e-mail addresses? What does the Web actually look like? How big is the Web? For all these questions and more, the course will provide a mixture of both mathematical models and real-world, hands-on labs. This course can be combined with CS/

EE 143 and CS/EE 145 to satisfy project requirement for CS undergraduate degree. Instructor: Wierman.

CS/EE 145. Projects in Networking. *9 units (0-0-9); third term. Prerequisite: CS/EE 143, CS/EE 144.* Students are expected to execute a substantial project in networking, write up a report describing their work, and make a presentation. This course can be combined with CS/EE 143 and CS/EE 144 to satisfy the project requirement for CS undergraduate degree. Instructors: Low, Wierman.

CS/EE 146. Advanced Networking. *9 units (3-3-3); second term. Prerequisite: CS/EE 143 or instructor's permission.* This is a research-oriented course meant for undergraduates and beginning graduate students who want to learn about current research topics in communication networks. The topics covered in the course will vary, but will be pulled from current research topics in the design, analysis, control, and optimization of networks, protocols, and Internet applications. Usually offered in alternate years. Instructor: Low.

CS/EE 147. Network Performance Analysis. *9 units (3-0-6); third term. Prerequisite: Ma 2 ab is required. CS/EE 143, CS/EE 144, and ACM 116 are recommended.* When designing a network protocol, distributed system, etc., it is essential to be able to quantify the performance impacts of design choices along the way. For example, should we invest in more buffer space or a faster processor? One fast disk or multiple slower disks? How should requests be scheduled? What dispatching policy will work best? Ideally, one would like to make these choices before investing the time and money to build a system. This class will teach students how to answer this type of "what if" question by introducing students to analytic performance modeling, the tools necessary for rigorous system design. The course will focus on the mathematical tools of performance analysis (which include stochastic modeling, scheduling theory, and queueing theory) but will also highlight applications of these tools to real systems. Usually offered in alternate years. Instructor: Wierman.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS 150. Probability and Algorithms. *9 units (3-0-6); second term. Prerequisites: CS 38 a and Ma 5 abc.* Elementary randomized algorithms and algebraic bounds in communication, hashing, and identity testing. Game tree evaluation. Topics may include randomized parallel computation; independence, k-wise independence and derandomization; rapidly mixing Markov chains; expander graphs and their applications; clustering algorithms. Instructor: Schulman.

CS 151. Complexity Theory. *9 units (3-0-6); 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 2009–10.

CS 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. Offered in alternate years. Instructor: Umans.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3); first term. Prerequisites: Ma 2 b or equivalent; and CS 1 or equivalent.* How can we build systems that perform well in unknown environments and unforeseen situations? How can we develop systems that exhibit "intelligent" behavior, without prescribing explicit rules? How can we build systems that learn from experience in order to improve their performance? We will study core modeling techniques and algorithms from statistics, optimization, logic planning, and control and study applications in areas such as sensor networks, robotics, and the Internet. The course is designed for upper-level undergraduate and graduate students, and will provide hands-on experience in a course project. Instructor: Krause. Not offered in 2009–10.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3); first term. Prerequisites: background in algorithms and statistics (CS/CNS/EE 154 or CS/CNS/EE 156 a or instructor's permission).* Many real-world problems in AI, computer vision, robotics, computer systems, computational neuroscience, computational biology, and natural language processing require one to reason about highly uncertain, structured data, and draw global insight from local observations. Probabilistic graphical models allow addressing these challenges in a unified framework. These models generalize approaches such as hidden Markov models and Kalman filters, factor analysis, and Markov random fields. In this course, we will study the problem of learning such models from data, performing inference (both exact and approximate), and using these models for making decisions. The techniques draw from statistics, algorithms, and discrete and convex optimization. The course will be heavily research oriented, covering current developments such as probabilistic relational models, models for naturally combining logical and probabilistic inference, and nonparametric Bayesian methods. Instructor: Krause.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6); first, second 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.

CS/CNS/EE 159. Projects in Machine Learning and AI. *9 units (0-0-9); third term. Prerequisite: CS/CNS/EE 154 or CS/CNS/EE 156 b.* Students are expected to execute a substantial project in AI and/or machine learning, write up a report describing their work, and make a presentation. This course can be combined with CS/CNS/EE 154/155 or with CS/CNS/EE 156 ab to satisfy the project requirement for the CS undergraduate degree. Instructor: Krause. Not offered 2009–10.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3); first term. Prerequisites: Ma 2 and extensive programming experience.* This course introduces the basic ideas behind computer graphics and its fundamental algorithms. Topics include graphics input and output, the graphics pipeline, sampling and image manipulation, three-dimensional transformations and interactive modeling, basics of physically based modeling and animation, simple shading models and their hardware implementation, and fundamental algorithms of scientific visualization. Students will be required to perform significant implementations. Instructor: Barr.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3); third term. Prerequisites: Ma 2 and CS/CNS 171 or instructor's permission.* This laboratory class offers students an opportunity for independent work covering recent computer graphics research. In coordination with the instructor, students select a computer graphics modeling, rendering, interaction, or related algorithm and implement it. Students are required to present their work in class and discuss the results of their implementation and any possible improvements to the basic methods. May be repeated for credit with instructor's permission. Instructor: Barr.

CS 176. Introduction to Computer Graphics Research. *9 units (3-3-3); second term. Prerequisite: CS/CNS 171, or 173, or 174.* The course will go over recent research results in computer graphics, covering subjects from mesh processing (acquisition, compression, smoothing, parameterization, adaptive meshing), simulation for purposes of animation, rendering (both photo- and nonphotorealistic), geometric modeling primitives (image based, point based), and motion capture and editing. Other subjects may be treated as they appear in the recent literature. The goal of the course is to bring students up to the frontiers of computer graphics research and prepare them for their own research. Instructor: Desbrun.

CS 177. Discrete Differential Geometry: Theory and Applications. *9 units (3-3-3); first term.* Topics include, but are not limited to, discrete exterior calculus; Whitney forms; DeRham and Whitney complexes; Morse theory; computational and algebraic topology; discrete simulation of thin shells, fluids, electromagnetism, elasticity; surface parameterization; Hodge decomposition. Instructor: Desbrun.

CS 180. Master's Thesis Research. *Units (total of 45) are determined in accordance with work accomplished.*

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3); first, second, third terms.* Digital integrated system design, with projects involving the design, verification, and testing of high-complexity CMOS microcircuits. First-term lecture and homework topics emphasize disciplined design, and include CMOS logic, layout, and timing; computer-aided design and analysis tools; and electrical and performance considerations. Each student is required in the first term to complete individually the design, layout, and verification of a moderately complex integrated circuit. Advanced topics second and third terms include self-timed design, computer architecture, and other topics that vary year by year. Projects are large-scale designs done by teams. Not offered 2009–10.

CS/EE 184 ab. Computer Architecture. *9 units (3-3-3); second, third terms. Prerequisites: CS 21 and CS 24, or instructor's permission.* Organization and design of physical computational systems, basic building blocks for computations, understanding and exploiting structure in computational problems, design space, costs, and trade-offs in computer organization, common machine abstractions, and implementation/optimization techniques. The course will develop the fundamental issues and trade-offs that define computer organizational and architectural styles, including RISC, VLIW, Super Scalar, EPIC, SIMD, Vector, MIMD, reconfigurable, FPGA, PIM, and SoC. Basic topics in the design of computational units, instruction organization, memory systems, control and data flow, interconnect, and the hardware-software abstraction will also be covered. Not offered 2009–10.

CS 185 abc. Asynchronous VLSI Design Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisite: CS 139.* The design of digital integrated circuits whose correct operation is independent of delays in wires and gates. (Such circuits do not use clocks.) Emphasis is placed on high-level synthesis, design by program transformations, and correctness by construction. The first term introduces delay-insensitive design techniques, description of circuits as concurrent programs, circuit compilation, standard-cell layout and other computer-aided design tools, and electrical optimizations. The second term is reserved for advanced topics, and for the presentation and review of mid-size projects, which will be fabricated in CMOS or GaAs technologies, and tested. Instructor: Martin. Part c not offered 2009–10.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

SS/CS 241 ab. Introduction to Social and Information Sciences. *9 units (3-0-6).* For course description, see Social Science.

CS/EE 245. Special Topics in Networking. *9 units (3-3-3); second or third term. Prerequisites: CS/EE 143 and CS/EE 144 or instructor's permission.* This course is an advanced, research-oriented seminar in communication networks meant for graduate students and advanced undergraduates. The topics covered in the course will vary, but will always come from the cutting edge of networking research. Examples of possible topics are error-correcting codes, wireless networking, scheduling theory, and congestion control. Instructor: Staff. Not offered 2009–10.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3).* This course is an advanced, research-oriented seminar in machine learning and AI meant for graduate students and advanced undergraduates. The topics covered in the course will vary, but will always come from the cutting edge of machine learning and AI research. Examples of possible topics are active learning and optimized information gathering, AI in distributed systems, computational learning theory, machine learning applications (on the Web, in sensor networks and robotics). Instructor: Krause.

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 2009–10.

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.*

CDS 90 abc. Senior Thesis in Control and Dynamical Systems. *9 units (0-0-9); first, second, third terms. Prerequisites: CDS 110 ab or CDS 140 ab (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: Marsden.

CDS 101. Design and Analysis of Feedback Systems. *6 units (2-0-4); first term. Prerequisites: Ma 1 and Ma 2 or equivalents.* An introduction to feedback and control in physical, biological, engineering, and information sciences. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, modeling and model reduction, linear vs. nonlinear models, and local vs. global behavior. This course is taught concurrently with CDS 110 a, but is intended for students who are interested primarily in the concepts and tools of control theory and not the analytical techniques for design and synthesis of control systems. Instructor: MacMynowski.

CDS 104. Introductory Concepts for Dynamical Systems. *6 units (2-0-4); third term. Prerequisites: Ma 1, Ma 2 (or equivalent).* This course teaches basic concepts in mathematics and dynamics that are required for CDS 110 and CDS 140. It is intended as a tutorial for nonmajors who plan to do further course work in CDS but may not have adequate preparation in linear algebra and ordinary differential equations. Topics to be covered include linear ODEs in one variable, linear algebra, eigenvalues and eigenvectors, coupled linear ODEs, stability of OEDs. Extensive use of examples based on modeling of physical, biological, and information systems using differential equations and linear algebra. Instructor: Staff.

CDS 110 ab. Introductory Control Theory. *12 units (3-0-9) first, 9 units (3-0-6) second terms. Prerequisites: Ma 1 and Ma 2 or equivalents; ACM 95/100 may be taken concurrently.* An introduction to analysis and design of feedback control systems, including classical control theory in the time and frequency domain. Modeling of physical, biological, and information systems using linear and nonlinear differential equations. Stability and performance of interconnected systems, including use of block diagrams, Bode plots, the Nyquist criterion, and Lyapunov functions. Robustness and uncertainty management in feedback systems through stochastic and deterministic methods. Introductory random processes, Kalman filtering, and norms of signals and systems. The first term of this course is taught concurrently with CDS 101, but includes additional lectures, reading, and homework that is focused on analytical techniques for design and synthesis of control systems. Instructor: MacMynowski.

CDS 140 ab. Introduction to Dynamics. *9 units (3-0-6); first, second terms. Prerequisite: ACM 95 or equivalent.* Basics in topics in dynamics in Euclidean space, including equilibria, stability, Lyapunov functions, periodic solutions, Poincaré-Bendixon theory, Poincaré maps. Attractors and structural stability. The Euler-Lagrange equations, mechanical systems, small oscillations, dissipation, energy as a Lyapunov function, conservation laws. Introduction to simple bifurcations and eigenvalue crossing conditions. Discussion of bifurcations in applications, invariant manifolds, the method of averaging, Melnikov's method, and the Smale horseshoe. Instructors: Marsden, staff.

CDS 190. Independent Work in Control and Dynamical Systems. *Units to be arranged; first, second, third terms; maximum two terms. Prerequisite: CDS 110 ab or CDS 140 ab.* Research project in control and dynamical systems, supervised by a CDS faculty member.

CDS 201. Linear Algebra and Applied Operator Theory. *9 units (3-0-6); first term.* Linear spaces, subspaces, spans of sets, linear independence, bases, dimensions; linear transformations and operators, examples, nullspace/kernel, range-space/image, one-to-one and onto, isomorphism and invertibility, rank-nullity theorem; products of linear transformations, left and right inverses, generalized inverses. Adjoints of linear transformations, singular-value decomposition and Moore-Penrose inverse; matrix representation of linear transformations between finite-dimensional linear spaces, determinants, multilinear forms; metric spaces: examples, limits and convergence of sequences, completeness, continuity, fixed-point (contraction) theorem, open and closed sets, closure; normed and Banach spaces, inner product and Hilbert spaces: examples, Cauchy-Schwarz inequality, orthogonal sets, Gram-Schmidt orthogonalization, projections onto subspaces, best approximations in subspaces by projection; bounded linear transformations, principle of superposition for infinite series, well-posed linear problems, norms of operators and matrices, convergence of sequences and series of operators; eigenvalues and eigenvectors of linear operators, including their properties for self-adjoint operators, spectral theorem for self-adjoint and normal operators; canonical representations of linear operators (finite-dimensional case), including diagonal and Jordan form, direct sums of (generalized) eigenspaces. Schur form; functions of linear operators, including exponential, using diagonal and Jordan forms, Cayley-Hamilton theorem. Taught concurrently with ACM 104. Instructor: Beck.

CDS 202. Geometry of Nonlinear Systems. *9 units (3-0-6); second term. Prerequisite: CDS 201 or AM 125 a.* Basic differential geometry, oriented toward applications in control and dynamical systems. Topics include smooth manifolds and mappings, tangent and normal bundles. Vector fields and flows. Distributions and Frobenius's theorem. Matrix

Lie groups and Lie algebras. Exterior differential forms, Stokes' theorem. Instructor: Marsden.

CDS 205. Geometric Mechanics. *9 units (3-0-6); third term. Prerequisites: CDS 202, CDS 140.* The geometry and dynamics of Lagrangian and Hamiltonian systems, including symplectic and Poisson manifolds, variational principles, Lie groups, momentum maps, rigid-body dynamics, Euler-Poincaré equations, stability, and an introduction to reduction theory. More advanced topics (taught in a course the following year) will include reduction theory, fluid dynamics, the energy momentum method, geometric phases, bifurcation theory for mechanical systems, and nonholonomic systems. Given in alternate years; not offered 2009–10.

CDS 212. Introduction to Modern Control. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 abc or equivalent; CDS 110 ab or equivalent.* Introduction to modern control systems with emphasis on the role of control in overall system analysis and design. Examples drawn from throughout engineering and science. Open versus closed loop control. State-space methods, time and frequency domain, stability and stabilization, realization theory. Time-varying and nonlinear models. Uncertainty and robustness. Instructor: Doyle.

CDS 213. Robust Control. *9 units (3-0-6); second term. Prerequisites: CDS 212, CDS 201.* Linear systems, realization theory, time and frequency response, norms and performance, stochastic noise models, robust stability and performance, linear fractional transformations, structured uncertainty, optimal control, model reduction, m analysis and synthesis, real parametric uncertainty, Kharitonov's theorem, uncertainty modeling. Instructor: Doyle.

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 280. Advanced Topics in Geometric Mechanics or Dynamical Systems Theory. *Hours and units by arrangement. Prerequisite: instructor's permission.* Topics will vary according to student and instructor interest. Examples include chaotic transport theory, invariant manifold techniques, multidimensional geometric perturbation theory, the dynamics of coupled oscillators, rigid-body dynamics, numerical methods in dynamical systems theory. May be repeated for credit. Instructor: Marsden.

CDS 300 abc. Research in Control and Dynamical Systems. *Hours and units by arrangement.* Research in the field of control and dynamical systems. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructor: Staff.

ECONOMICS

Ec 11. Introduction to Economics. *9 units (3-2-4); first, third 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/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4).* For course description, see Business Economics and Management.

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. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visiting lecturers.

Ec 105. Industrial Organization. *9 units (3-0-6). Prerequisite: 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 in detail. Instructor: Iaryczower.

Ec 106. Topics in Applied Industrial Organization. *9 units (3-0-6); third term. Prerequisite: Ec 11; Ec 116 recommended.* Topics include simulation of mergers in oligopolistic industries, valuation of intellectual property, price setting and concentration in the pharmaceutical market, and statistical analysis of combined tobacco and asbestos exposure. A term paper will be required. Not offered 2009–10.

Ec 116. Contemporary Socioeconomic Problems. *9 units (3-0-6); first term. Prerequisites: Ec 11 and PS 12 or equivalents.* An analytical investigation of the economic aspects of certain current social issues. Topics: the economics of education, medical-care systems, urban affairs, and the welfare system. Not offered 2009–10.

Ec 118. Environmental Economics. *9 units (3-0-6); third term. Prerequisite: Ec 11 or equivalent.* This course provides a survey from the perspective of economics of public policy issues regarding the management of natural resources and the protection of environmental quality. The course covers both conceptual topics and recent and current applications. Included are principles of environmental and resource economics, management of nonrenewable and renewable resources, and environmental policy with the focus on air pollution problems, both local problems (smog) and global problems (climate change). Instructor: Ledyard.

Ec 121 ab. Theory of Value. *9 units (3-0-6); first, second terms. Prerequisites: Ec 11 and Ma 2 (may be taken concurrently).* A study of consumer preference, the structure and conduct of markets, factor pricing, measures of economic efficiency, and the interdependence of markets in reaching a general equilibrium. Instructor: Border.

Ec 122. Econometrics. *9 units (3-0-6); first term. Prerequisite: Ma 112 a.* The application of statistical techniques to the analysis of economic data. Instructor: Sherman.

Ec 123. Macroeconomics. *9 units (3-0-6); third term. Prerequisite: Ec 11 and modest ability to program in Matlab or Mathematica.* The role of time and uncertainty in understanding the behavior of economic aggregates such as investment, employment, and price levels. Emphasis is on representative-agent recursive equilibrium models. Topics include practical dynamic programming; job search, matching, and unemployment; asset pricing; monetary and fiscal policy; and taxation and insurance. Not offered 2009–10.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6); second term. Prerequisite: Ec 11 or SS 13.* An examination of certain analytical and quantitative tools and their application to American economic development. Instructor: Rosenthal.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Industrial Revolution. *9 units (3-0-6). Prerequisite: Ec 11 or SS 13.* Employs the theoretical and quantitative techniques of economics to help explore and explain the development of the European cultural area between 1000 and 1850. Topics include the rise of commerce, the demographic transition, the industrial revolution, and changes in property rights and capital markets. Not offered 2009–10.

Ec 131. Market Design. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* This course studies the design of markets, focusing on efficient organizations and the incentives created by market rules. Applications include online auction markets, government auctions of natural resources, matching markets (e.g., students to classes or schools or kidneys to recipients), and electricity and gas markets. It will examine the details of real-world markets, using game theoretic analysis, empirical analysis, and experimental work. Not offered 2009–10.

Ec 132. Auctions. *9 units (3-0-6); second term. Prerequisite: Ec 11.* The course covers basic topics in auction theory (private and common value auctions, revenue equivalence, reserve prices, budget constraints, risk aversion, etc.) and discusses more advanced theory such as mechanism design, multi-unit auctions, and interdependent valuations. Experimental studies of auctions will be reviewed where appropriate. The course will also discuss practical considerations that arise when designing auctions to sell licenses in a particular industry. Instructor: Goeree.

Ec 140. Economic Progress. *9 units (3-0-6); third term. Prerequisites: Ec 11 and Ma 2; Ec 122 recommended.* This course examines the contemporary literature on economic growth and development from both a theoretical and historical/empirical perspective. Topics include a historical overview of economic progress and the lack thereof; simple capital accumulation models; equilibrium/planning models of accumulation; endogenous growth models; empirical tests of convergence; the measurement and role of technological advancement; and the role of trade, institutions, property rights, human capital, and culture. Instructors: Border, Hoffman. Given in alternate years; offered 2009–10.

Ec 145. Public Finance. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Not offered 2009–10.

BEM/Ec 146. Organization Design. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3).* 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.

PS/Ec 173. Cooperation and Social Behavior. *9 units (3-0-6).* For course description, see Political Science.

Ec 181. Convex Analysis and Economic Theory. *9 units (3-0-6); second term. Prerequisites: Ma 2 ab, Ec 121 a.* Introduction to the use of convex analysis in economic theory. Includes a rigorous discussion of separating hyperplane theorems, continuity and differentiability properties of convex and concave functions, support functions, subdifferentials, Fenchel conjugacy, saddle-point theory, theorem of the alternative, and linear programming. Emphasis is on the finite-dimensional case, but infinite-dimensional spaces will be discussed. Applications to the theory of cost and production functions, decision theory, and game theory. Instructor: Border.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6).* For course description, see Business Economics and Management.

BEM/Ec 186. Political Economy of Financial Markets. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec/PS 190. Undergraduate Research. *Units to be arranged; any term. Prerequisite: advanced economics course and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research in political science or economics. Graded pass/fail.

ELECTRICAL ENGINEERING

EE 1. Introduction to Electrical Engineering Seminar. *1 unit; second term*. Required for EE undergraduates. Weekly seminar given by faculty in the department broadly describing different areas of electrical engineering: circuits and VLSI, communications, control, devices, images and vision, information theory, learning and pattern recognition, MEMS and micromachining, networks, electromagnetics and opto-electronics, RF and microwave circuits and antennas, robotics and signal processing, and specifically, research going on at Caltech. Instructor: Staff.

EE 5. Introduction to Embedded Systems. *6 units (2-3-1); first term.* This course is intended to give the student a basic understanding of the major hardware and software principles involved in the specification and design of embedded systems. Topics include basic digital logic, CPU and embedded system architecture, and embedded systems programming principles (events, user interfaces, and multitasking). The class is intended for students who wish to gain a basic understanding of embedded systems or for those who would like an introduction to the material before taking EE/CS 51/52. Graded pass/fail. Instructor: George.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2).* For course description, see Applied Physics.

EE 40. Semiconductor Sensors and Actuators. *9 units (3-0-6); third term. Prerequisites: APh/EE 9 ab, Ma 2 a.* This course provides an introduction to various sensors and actuators. The fundamental principles of the devices will be emphasized, together with their electrical implementation, such as biasing and signal processing circuits. Devices that will be discussed include optical sensors, solar cells, CCDs, CMOS imagers, temperature sensors, magnetic sensors, mechanical sensors, acoustic sensors (microphones), speakers, electrical generators, motors, etc. Instructor: Tai.

EE 45. Electronics Laboratory. *12 units (3-3-6); third term. Prerequisites: should be taken concurrently with EE 40, or instructor's permission; Ma 2 a, Ph 1abc.* Fundamentals of electronics and circuit analysis. Lectures and laboratory sessions on linear circuits, transient response, steady-state sinusoidal response and phasors, transformers, diodes, transistors, small-signal analysis, gain stages, operational amplifiers; an introduction to electrical and analog electronic systems such as radio and audio systems. Instructor: Emami.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3); first term.* The principles and design of microprocessor-based computer systems. Lectures cover both hardware and software aspects of microprocessor system design such as interfacing to input and output devices, user interface design, real-time systems, and table-driven software. The homework emphasis is on software development, especially interfacing with hardware, in assembly language. Instructor: George.

EE/CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0); second term. Prerequisite: EE/CS 51 or equivalent.* The student will design, build, and program a specified microprocessor-based system. This structured laboratory is organized to familiarize the student with electronic circuit construction techniques, modern development facilities, and standard design techniques. The lectures cover topics in microprocessor system design such as display technologies, interfacing with analog systems, and programming microprocessors in high-level languages. Instructor: George.

EE/CS 53 abc. Microprocessor Project Laboratory. *12 units (0-12-0); first, second, third terms. Prerequisite: EE/CS 52 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. Instructor: George.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or up to 18 units (2-15-1) third term.* For course description, see Computer Science.

EE 80 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained during the junior year to allow sufficient time for planning the research.* Individual research project, carried out under the supervision of a member of the electrical engineering or computer science faculty. Project must include significant design effort. Written report required. Open only to senior electrical engineering, computer science, or electrical and computer engineering majors. Not offered on a pass/fail basis. Instructor: Potter.

EE 90. Analog Electronics Project Laboratory. *9 units (1-8-0); third term. Prerequisites: EE 40 and EE 45.* A structured laboratory course that gives the student the opportunity to design and build a sequence of simple analog electronics projects. The goal is to gain familiarity with circuit design and construction, component selection, CAD support, and debugging techniques. Instructor: Megdal.

EE 91 ab. Experimental Projects in Electronic Circuits. *Units by arrangement; first, second terms. 12 units minimum each term. Prerequisites: EE 45. Recommended: EE/CS 51 and 52, and EE 114 ab (may be taken concurrently). Open to seniors; others only with instructor's permission.* An opportunity to do advanced original projects in analog or digital electronics and electronic circuits. Selection of significant projects, the engineering approach, modern electronic techniques, demonstration and review of a finished product. DSP/microprocessor development support and analog/digital CAD facilities available. Text: literature references. Instructor: Megdal.

EE 99. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering will be arranged. For undergraduates; students should consult with their advisers. Graded pass/fail.

EE 105 abc. Electrical Engineering Seminar. *1 unit; first, second, third terms.* All candidates for the M.S. degree in electrical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Hassibi.

EST/EE/ME 109 ab. Energy. *9 units(3-0-6.)* For course description, see Energy Science and Technology.

EE 111. Signals, Systems, and Transforms. *9 units (3-0-6); first term. Prerequisites: Ma 1, Ma 2. EE 45 recommended.* An introduction to continuous and discrete time signals and systems. Study of the Fourier transform, Fourier series, the Laplace transform, Z-transforms, and the fast Fourier transform as applied in electrical engineering. Various types of systems, with emphasis on linear and time invariant systems. Transfer functions, difference and differential equations, state space representations, system realizations with block diagrams, and analysis of transient and steady state responses. Sampling theorems for analog to digital conversion. Instructor: Vaidyanathan.

EE 112. Introduction to Digital Signal Processing. *9 units (3-0-6); second term. Prerequisites: EE 111 or equivalent.* Fundamentals of digital signal processing, digital representations, analog to digital conversions, fast Fourier transformation, digital filtering, filter structures, quantization and stability analysis, roundoff noise calculations, and applications in various areas. Instructor: Vaidyanathan. Given in alternate years; not offered 2009–10.

EE 113. Feedback and Control Circuits. *12 units (4-4-4); third term. Prerequisite: 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 build, analyze, test, and measure the circuits and systems discussed in the lectures. Instructor: George.

EE 114 ab. Analog Circuit Design. *12 units (4-0-8); first, second terms. Prerequisite: EE 45 or equivalent, EE 114 a or equivalent.* Analysis and design of analog circuits at the transistor level. Emphasis on intuitive design methods, quantitative performance measures, and practical circuit limitations. Circuit performance evaluated by hand calculations and computer simulations. Recommended for seniors and graduate students. First term deals with continuous time and amplitude signals; physics of bipolar and MOS transistors, low-frequency behavior of single-stage and multistage amplifiers, current sources, active loads, differential amplifiers, operational amplifiers, and supply and temperature independent biasing. Second term covers high-frequency response of amplifiers, feedback in electronic circuits, stability of feedback amplifiers, and noise in electronic circuits. A number of the following topics will be covered each year: translinear circuits, switched capacitor circuits, data conversion circuits (A/D and D/A), continuous-time $G_m.C$ filters and phase locked loops. Instructor: Analui.

ACM/EE 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

Ph/EE 118 ab. Low-Noise Electronic Measurement. *9 units (3-0-6).* For course description, see Physics.

EE 119 abc. Advanced Digital Systems Design. *9 units (3-3-3); first, second, third terms. Prerequisites: EE/CS 52 or CS/EE 181 a.* Advanced digital design as it applies to the design of systems using PLDS and ASICs (in particular, gate arrays and standard cells). The course covers both design and implementation details of various systems and logic device technologies. The emphasis is on the practical aspects of ASIC design, such as timing, testing, and fault grading. Topics include synchronous design, state machine design, ALU and CPU design, application-specific parallel computer design, design for testability, PALs, FPGAs, VHDL, standard cells, timing analysis, fault vectors, and fault grading. Students are expected to design and implement both systems discussed in the class as well as self-proposed systems using a variety of technologies and tools. Instructor: George.

EE 124. Mixed-mode Integrated Circuits. *9 units (3-0-6); third term. Prerequisite: EE 114 a or equivalent.* Introduction to selected topics in mixed-signal circuits and systems in highly scaled CMOS technologies. Design challenges and limitations in current and future technologies will be discussed through topics such as clocking (PLLs and DLLs), clock distribution networks, sampling circuits, high-speed transceivers, timing recovery techniques, equalization, monitor circuits, power delivery, and converters (A/D and D/A). A design project is an integral part of the course. Instructor: Emami.

EE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0); second term. Prerequisite: Basic knowledge of digital electronics.* Study of programmable logic devices (CPLDs and FPGAs). Detailed study of the VHDL language, with basic and advanced applications. Review and discussion of digital design principles for combinational-logic, 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. Not offered 2009–10.

EE/Ma 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisite: Ma 2.* Shannon's mathematical theory of communication, 1948–present. Entropy, relative entropy, and mutual information for discrete and continuous random variables. Shannon's source and channel coding theorems. Mathematical models for information sources and communication channels, including memoryless, first-order Markov, ergodic, and Gaussian. Calculation of capacity-cost and rate-distortion functions. Kolmogorov complexity and universal source codes. Side information in source coding and communications. Network information theory, including multiuser data compression, multiple access channels, broadcast channels, and multiterminal networks. Discussion of philosophical and practical implications of the theory. This course, when combined with EE 112, EE/Ma/CS 127, EE 161, and/or EE 167 should prepare the student for research in information theory, coding theory, wireless communications, and/or data compression. Instructor: Effros.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6); third term. Prerequisite: Ma 2.* This course, a sequel to EE/Ma 126 a, may be taken independently; it will develop 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, Golay, Fire, 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, fountain coding. Emphasis will be placed on the associated encoding and decoding algorithms, and students will be asked to demonstrate their understanding with a software project. Instructor: Ho.

EE 128 ab. Selected Topics in Digital Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: EE 111 and EE 160 or equivalent required, and EE 112 or equivalent recommended.* The course focuses on several important topics that are basic to modern signal processing. Topics include multirate signal processing material such as decimation, interpolation, filter banks, polyphase filtering, advanced filtering structures and nonuniform sampling, optimal statistical signal processing material such as linear prediction and antenna array processing, and signal processing for communication including optimal transceivers. Instructor: Vaidyanathan.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6).* For course description, see Applied Physics.

EE/APh 131. Optical Wave Propagation. *9 units (3-0-6); second term.* This course focuses on optical wave propagation and related applications. Topics to be covered include Huygens' principle, Fourier optics, Gaussian waves, imaging, gratings, spectroscopy, interferometry, Fabry-Perot cavities, coherence, holography, femtosecond optics, dispersion, Kramers-Kronig relation, Mie scattering theory, photonic band gaps, and near-field imaging. Instructor: Crosignani.

APh/EE 132. Optoelectronic Materials and Devices. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 143. Communication Networks. *9 units (3-3-3).* For course description, see Computer Science.

CS/EE 144. Ideas behind the Web. *9 units (3-0-6).* For course description, see Computer Science.

CS/EE 145. Projects in Networking. *9 units (0-0-9).* For course description, see Computer Science.

CS/EE 146. Advanced Networking. *9 units (3-3-3).* For course description, see Computer Science.

CS/EE 147. Network Performance Analysis. *9 units (3-0-6).* For course description, see Computer Science.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6); first, third terms. 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 151. Electronic Engineering. *9 units (3-0-6); second term. Prerequisite: EE 45.* Foundations of circuit theory—electric fields, magnetic fields, transmission lines, and Maxwell's equations, with engineering applications. Instructor: Rutledge.

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.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second terms. Prerequisite: Ph 2 or equivalent.* An overview of the physics behind space remote sensing instruments. Topics include the interaction of electromagnetic waves with natural surfaces, including scattering of microwaves, microwave and thermal emission from atmospheres and surfaces, and spectral reflection from natural surfaces and atmospheres in the near-infrared and visible regions of the spectrum. The class also discusses the design of modern space sensors and associated technology, including sensor design, new observation techniques, ongoing developments, and data interpretation. Examples of applications and instrumentation in geology, planetology, oceanography, astronomy, and atmospheric research. Instructor: van Zyl.

CS/CNS/EE 159. Projects in Machine Learning and AI. *9 units (0-0-9).* For course description, see Computer Science.

EE 160. Communication-System Fundamentals. *9 units (3-0-6); second term. Prerequisite: EE 111.* Laws of radio and guided transmission, noise as a limiting factor, AM and FM signals and signal-to-noise ratio, sampling and digital transmission, errors, information theory, error correction. Emphasis will be on fundamental laws and equations and their use in communication-system designs, including voice, video, and data. Instructor: Hassibi.

EE 161. Wireless Communications. *9 units (3-0-6); third term. Prerequisite: EE 160.* This course will cover the fundamentals of wireless channels and channel models, wireless communication techniques, and wireless networks. Topics include statistical models for time-varying narrowband and wideband channels, fading models for indoor and outdoor systems, macro- and microcellular system design, channel access and spectrum sharing using TDMA, FDMA, and CDMA, time-varying channel capacity and spectral efficiency, modulation and coding for wireless channels, antenna arrays, diversity combining and multiuser detection, dynamic channel allocation, and wireless network architectures and protocols. Not offered 2009–10.

EE 163 ab. Communication Theory. *9 units (3-0-6); second, third terms. Prerequisite: EE 111; ACM/EE 116 or equivalent.* Least mean square error linear filtering and prediction. Mathematical models of communication processes; signals and noise as random processes; sampling and quantization; modulation and spectral occupancy; intersymbol interference and synchronization considerations; signal-to-noise ratio and error probability; optimum demodulation and detection in digital baseband and carrier communication systems. Instructors: Ho, Quirk.

EE 164. Stochastic and Adaptive Signal Processing. *9 units (3-0-6); third term. Prerequisite: ACM/EE 116 or equivalent.* Fundamentals of linear estimation theory are studied, with applications to stochastic and adaptive signal processing. Topics include deterministic and stochastic least-squares estimation, the innovations process, Wiener filtering and spectral factorization, state-space structure and Kalman filters, array and fast array algorithms, displacement structure and fast algorithms, robust estimation theory and LMS and RLS adaptive fields. Instructor: Hassibi.

EE/BE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5); third term. Prerequisite: EE 151 or equivalent.* Topics include Fourier optics, scattering theories, shot noise limit, energy transitions associated with fluorescence, phosphorescence, and Raman emissions. Study of coherent anti-Stokes Raman spectroscopy (CARS), second harmonic generation and near-field excitation. Scattering, absorption, fluorescence, and other optical properties of biological tissues and the changes in these properties during cancer progression, burn injury, etc. Specific optical technologies employed for biomedical research and clinical applications: optical coherence tomography, Raman spectroscopy, photon migration, acousto-optics (and opto-acoustics) imaging, two photon fluorescence microscopy, and second- and third-harmonic microscopy. Instructor: Yang.

EE 167. Data Compression. *9 units (3-0-6); third term. Prerequisite: EE/Ma 126 or instructor's permission.* An introduction to the basic results, both theoretical and practical, of data compression. Review of relevant background from information theory. Fixed model and adaptive Huffman and arithmetic codes. The Lempel-Ziv algorithm and its variants. Scalar and vector quantization, including the Lloyd-Max quantizers, and the generalized Lloyd algorithm. Transform coding. Karhuenen-Loeve and discrete cosine transforms. The bit allocation problem. Subband coding. Practical algorithms for image and video compression. Not offered 2009–10.

EE/APh 180. Solid-State Devices. *9 units (3-0-6); second term. Prerequisite: EE 45.* Starting with the phenomenological statement of physical processes, the operation of a device is derived from fundamental principles and the device's materials and design. Subjects include the motion of charge carriers in solids, equilibrium statistics, the electronic structure of solids, doping, nonequilibrium states, the pn junction, the junction transistor, the Schottky diode, the field-effect transistor, the light-emitting diode, and the photodiode. Not offered 2009–10.

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 184 ab. Computer Architecture. *9 units (3-3-3).* For course description, see Computer Science.

EE/BE 185. MEMS Technology and Devices. *9 units (3-0-6); first term. Prerequisites: 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 2009–10.

CNS/Bi/EE 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

EE 187. VLSI and ULSI Technology. *9 units (3-0-6); first 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. Instructor: Tai.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/EE 189. Design and Construction of Biodevices. *12 units (3-6-3).* For course description, see Bioengineering.

EE 226. Advanced Information and Coding Theory. *9 units (3-0-6); first term.* A selection of topics in information theory and coding theory not normally covered in EE/Ma 126 ab or EE/Ma/CS 127. These topics include constrained noiseless codes, constructive coding theorems for erasure channels, density evolution, repeat-accumulate and related codes, and network coding. Not offered 2009–10.

EE 243 abc. Quantum Electronics Seminar. *6 units (3-0-3); first, second, third terms.* Advanced treatment of topics in the field of quantum electronics. Each weekly seminar consists of a review and discussion of results in the areas of quantum electronics and optoelectronics. Instructor: Yariv.

CS/EE 245. Special Topics in Networking. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3).* For course description, see Computer Science.

EE 291. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering. Primarily for graduate students; students should consult with their advisers.

ENERGY SCIENCE AND TECHNOLOGY

EST/EE/ME 109 ab. Energy. *9 units (3-0-6); first, second terms. Prerequisites: Ph 1 abc and Ma 2 ab.* Modeling and forecasting. Heating, transportation, and electricity demand. Historical energy sources: wood and whale oil. Fossil-fuel supplies: oil, natural gas, coal, oil sands, and oil shale. Alternative energy sources: hydroelectric, nuclear, wind, biomass, geothermal, biofuels, waves, ocean thermal, solar photovoltaic, and solar thermal. Thermodynamics of energy conversion: vapor power cycles, combustion, combined cycle, and fuel cells. Transportation systems: internal combustion engines, gas turbines, and electric vehicles. Energy systems: pipelines, rail and water transport, shipping, carbon capture and sequestration, transmission lines and electricity distribution networks. Energy policy: efficiency regulations, biofuels vs food, water impacts, air pollution, and climate. Instructors: Rutledge, Shepherd.

ME/EST 122 ab. Sustainable Energy Engineering. *9 units (3-0-6).* For course description, see Mechanical Engineering.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6).* For course description, see Materials Science.

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: Rosakis.

E 10. Technical Seminar Presentations. *3 units (1-0-2); first, second, third terms. (Seniors required to take E 10 are given priority in registration. NOTE: Those who neither preregister nor attend the organizational meeting may not be permitted to enroll.)* Guidance and practice in organizing and preparing topics for presentation and in speaking with the help of visual aids, including whiteboards, overhead projectors, and video projectors. Instructor: Fender.

E 11. Written Technical Communication in Engineering and Applied Science. *3 units (1-0-2); second, third terms.* This class provides the opportunity for students to gain experience in technical writing in engineering and applied science. Students will choose a technical topic of interest, possibly based on a previous research or course project, and write a paper in a form that would be appropriate as an engineering report, a technical conference paper, or a peer-reviewed journal paper. The topic of ethical considerations for engineers and scientists as they arise in the publication and peer review process will also be discussed. A Caltech faculty member, a postdoctoral scholar, or technical staff member serves as a technical mentor for each student, to provide feedback on the content and style of the report. *Fulfills the Institute scientific writing requirement.* Instructors: Pierce, Readhead.

E 102. Entrepreneurial Development. *9 units (3-0-6); second term.* An introduction to the basics of getting a high-technology business started, including early-stage patent, organizational, legal, and financing issues; growing a company; taking a company public; and mergers and acquisitions. Lectures include presentations by invited experts in various specialties and keynote guest lecturers of national stature in technology start-ups. Instructor: Pickar.

E/ME 103. Management of Technology. *9 units (3-0-6); third term.* A course intended for students interested in learning how rapidly evolving technologies are harnessed to produce useful products. Students will work through Harvard Business School case studies, supplemented by lectures to elucidate the key issues. There will be a term project. The course is team-based and designed for students considering working in companies (any size, including start-ups) or eventually going to business school. Topics include technology as a growth agent, financial fundamentals, integration into other business processes, product development pipeline and portfolio management, learning curves, risk assessment, technology trend methodologies (scenarios, projections), motivation, rewards and recognition. Industries considered will include electronics (hardware and software), aerospace, medical, biotech, etc. E 102 and E/ME 105 are useful but not required precursors. Not offered 2009–10.

E/ME 105. Product Design for the Developing World. *9 units (3-0-6); first term.* The course will emphasize products appropriate for the developing world—for those people subsisting on less than one dollar a day. The focus is on Guatemala and taught in partnership with Landivar University in Guatemala City and the Art Center College of Design in Pasadena. The class consists of mixed teams, with lectures teleconferenced between countries. The class teaches product design methodologies informed by the special circumstances of the end customers. Technologies chosen are typically indigenous not "high tech". Issues of sustainability in a business as well as in an engineering sense are included as are cultural concerns, ultra low cost, manufacturability and ergonomic design. Each team works on a product which addresses people's basic needs, e.g., potable water, clean burning stoves, food processing, ergonomic carriers. Instructor: Pickar.

E 150 abc. Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in applied mechanics, electrical engineering, materials science, and mechanical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Fultz.

ENGLISH

En 1 a. English Composition for ESL Writers. *9 units (3-0-6 or 4-0-5); first term.* An introduction to English composition for students whose first language is not English and who need focused instruction before taking a freshman humanities course. This course offers fundamental strategies for composing fluent standard written English and for constructing academic arguments. Students are assigned to En 1 a based on a writing assessment that is required of all incoming students. *Not available for credit toward the humanities–social science requirement.* Instructor: Geasland.

En 1 b. English Composition for ESL Writers. *9 units (3-0-6 or 4-0-5); second term.* Continuation of En 1 a for students who need additional instruction before taking a freshman humanities course. *Not available for credit toward the humanities–social science requirement.* Instructor: Geasland.

En 2. Introduction to College Writing. *9 units (2-2-5); first term.* A course in developing forceful academic essays, for students who need more focused attention to writing before entering freshman humanities courses. It emphasizes analytic and argumentative writing and critical reading. The class features small seminar discussions and weekly conferences with the instructor. Students are assigned to En 2 based on a writing assessment that is required of all incoming students. *Not available for credit toward the humanities–social science requirement.* Instructor: Staff.

Hum/En 5. Major British Authors. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 6. American Literature and Culture. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 7. Modern European Literature. *9 units (3-0-6).* For course description, see Humanities.

F/En 30. Introduction to Film. *9 units (3-0-6).* For course description, see Film.

En 84. Writing Science. *9 units (3-0-6), third term.* Instruction and practice in writing about science and technology for general audiences. The course considers how to convey complex technical information in clear, engaging prose that nonspecialists can understand and appreciate. Readings in different genres (e.g., magazine and newspaper journalism, reflective essays, case studies, popularizations) raise issues for discussion and serve as models for preliminary writing assignments and for a more substantial final project on a topic of each student's choice. Includes oral presentation. *Satisfies the Institute scientific writing requirement and the option oral communication requirement for humanities majors.* Instructor: Youra.

En 85. Writing Poetry. *9 units (3-0-6); third term.* Students will develop their poetic craft by creating poems in a variety of forms. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Students may apply one term of En 85, 86, 87, and 88 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Hall.

En 86. Fiction and Creative Nonfiction Writing. *9 units (3-0-6); second term.* The class is conducted as a writing workshop in the short-story and personal essay/memoir form. Modern literary stories and essays are discussed, as well as the art and craft of writing well, aspects of "the writing life," and the nature of the publishing world today. Students are urged to write fiction or nonfiction that reflects on the nature of life. Humor is welcome, although not genre fiction such as formula romance, horror, thrillers, fantasy, or sci-fi. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Gerber.

En 87. Writing Fiction: The Imaginary. *9 units (3-0-6); third term.* Students will develop their talents for writing imaginary short stories other than science fiction. A number of models will be proposed to them for inspiration, e.g., folk tales, tales of the supernatural, fables, stories of "magic realism," examples of surrealism and the "absurd," and so on. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructors: Hall, Magun.

En 88. Memoir: Writing the Self. *9 units (3-0-6); second term.* Whereas a diarist writes from an ever-moving present, the art of memoir demands remembering, standing far enough back to shape experience and give it meaning, to discover a "story line" one never suspected existed, to find continuity in seeming randomness. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Magun.

En 89. News Writing. *9 units (3-0-6).* This course teaches the basic skills of news gathering and reporting. Students learn how to research stories, conduct interviews, structure news articles, and produce balanced copy. They also work on developing concise and effective prose. In addition to writing several articles, assignments include reading and discussing material from professional newspapers as well as analyzing and editing the writing of peers. The course covers other topics relevant to responsible news writing, such as journalistic ethics, the tradition and responsibilities of free speech, and the social function of the press in a democracy. Affiliation with the *California Tech* is not a requirement for enrollment. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Staff.

En 92. Literature of the Holocaust. *9 units (3-0-6); third term.* Elie Wiesel has written: "At Auschwitz, not only man died, but also the idea of man . . . It was its own heart the world incinerated at Auschwitz." This class will explore the reverberation of this premise in the literature that grew out of the holocaust experience, as well as the shifting aesthetics of "holocaust literature" over the last half century. Put simply, can there be "an aesthetics of atrocity"? What are the responsibilities of art and literature to history? Should a perpetrator of genocide ever engage our moral imagination? In an attempt to grapple with these questions, students will read works, both fiction and nonfiction, by a range of authors, including Primo Levi, Elie Wiesel, Ida Fink, Cynthia Ozick, Tadeusz Borowski, Bernard Schlink, and W. G. Sebold. Not offered 2009–10.

En 93. Women on the Edge. *9 units (3-0-6); third term.* This class will consider how women's writing in the 20th century often flouts the conventional portrayal of woman as ministering angel preoccupied with the needs of family without much regard to her own. Writers to be read include Kate Chopin, Colette, Marguerite Duras, Sylvia Plath, Angela Carter, Jeanette Winterson, Toni Morrison, Elfriede Jelinek. Instructor: Magun. Not offered 2009–10.

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. 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 113 ab. Shakespeare's Career. *9 units (3-0-6).* A survey of Shakespeare's career as a dramatist. The first term will study his comedies and histories; the second, his tragedies and tragicomedies. Students will need to read one play per week. Instructor: Pigman.

En 114 ab. Shakespeare. *9 units (3-0-6); second term.* A close study of Shakespeare's plays with an emphasis on his language, dramatic structures, characters, and themes. Each term will concentrate on a detailed consideration of three or four of Shakespeare's major plays. The first term is not a prerequisite for the second. Instructor: La Belle.

En 116. Milton and the Epic Tradition. *9 units (3-0-6); third term.* Epic poetry is a competitive and self-referential genre. Virgil imitates and revises Homer, Dante makes Virgil his guide through hell and most of purgatory before leaving him behind, and Milton transforms the entire epic tradition. Since Milton's engagement with and criticism of the epic are essential elements of *Paradise Lost and Paradise Regained*, we will focus on his dialogue with Homer, Virgil, and Dante and their differing conceptions of heroism. Instructor: Pigman. Not offered 2009–10.

En 119. Displacement. *9 units (3-0-6); third term.* The literary fascination with people who change places, temporarily or permanently, over a short distance or across the globe, in works dating from our lifetimes and from the recent and the remote past. How readily can such stories be compared, how easy is it to apply traditional categories of literary evaluation, and, in the contemporary world, how have poetry and prose fictions about migration survived alongside other media? 21st-century works will receive considerable attention; other readings may include Virgil, Swift, Flaubert, Mann, Achebe, Nabokov, Didion, Morrison. Instructor: Haugen.

En 120. Books. *9 units (3-0-6).* This class examines not only the long history of book production in the West, but also the multifarious uses to which books have been put. Historical topics might include political advice manuals (Machiavelli), prophecies of world destruction (Nostradamus), and the cult of the national author (beginning with Shakespeare's fans in the 17th and 18th centuries); closer to our time, potential topics include scientific books that also became best sellers (Darwin and Freud), metafictions, and the rise of the book club. The emphasis is on the circulation of books as physical objects. Not offered 2009–10.

En 121. Literature and Its Readers. *9 units (3-0-6); first term.* The course will investigate readers who have made adventurous uses of their favorite works of literature, from Greek antiquity through the 20th century. Sometimes those readers count, at least temporarily, as literary critics, as when the philosopher Aristotle made Sophocles' *Oedipus the*

King the central model in his wildly successful essay on the literary form of tragedy. Other readers have been even more experimental, as when Sigmund Freud, studying the same play, made the "Oedipus complex" a meeting point for his theory of psychology, his vision of human societies, and his fascination with literary narrative. It will discuss some basic questions about the phenomenon of literary reading. Does a book have a single meaning? Can it be used rightly or wrongly? Instructor: Haugen.

En 122. The 18th-Century English Novel. *9 units (3-0-6); third term.* The realistic novel as 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 2009–10.

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 2009–10.

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 2009–10.

En 125. British Romantic Literature. *9 units (3-0-6); third 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: Staff.

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. Instructor: Staff.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); offered by announcement.* The development of Irish fiction, poetry, and drama from the early 20th-century Irish literary renaissance, through the impact of modernism, to the Field Day movement and other contemporary developments. Topics may include the impact of political violence and national division upon the literary imagination; the use of folk and fairy-tale traditions; patterns of emigration and literary exile; the challenge of the English language and the relation of Irish writing to British literary tradition; and recent treatments of Irish literature in regional, postcolonial, and global terms. Works by Joyce, Yeats, Synge, Friel, O'Brien, Heaney, Boland, and others. Instructor: Gilmartin.

En 129. Enlightenment Fiction. *9 units (3-0-6); third term.* What was the fate of fiction in an Age of Reason? Historians have questioned whether a conventional sense of the Enlightenment adequately accounts for European culture in the 18th century, and the literary imagination can seem particularly unsuited to generalizations about progress, optimism, reason, and social order. This course will consider experimental narratives and philosophical satires from the English and Continental tradition, as well as early Romantic responses to the Enlightenment. Readings may include Defoe, Sterne, Voltaire, Diderot, Mary Shelley, Hoffman, and fairy tales from the brothers Grimm. Not offered 2009–10.

En 130. Vital Signs: Literature and the Human Body. *9 units (3-0-6)*. A literary history of the human body, from the Renaissance to the present. Often overlooked in intellectual life, our bodies nevertheless play a crucial role in our everyday mental, emotional, and social experience. But the language of the body is difficult to read. With the aid of thinkers from Plato to Marx and Freud, as well as film and drama, students will explore the significance of the body through a wide range of poetry and fiction. We will consider the following questions: What can literature teach us about the body that science cannot? How does literature represent and communicate bodily experience? What is the relation between writing and performative arts such as singing and dancing, religious rituals, or sport? What is the fate of the body in a technologically advanced culture such as ours? Authors studied may include Shakespeare, Coleridge, Wordsworth, Mary Shelley, Keats, Dickinson, Whitman, Melville, Stein, Hughes, and Levi. Instructor: Baskin.

En 131. Poe's Afterlife. *9 units (3-0-6).* 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. Instructor: Weinstein.

En 132. American Literature Until the Civil War. *9 units (3-0-6); second term.* The course will analyze the literature of this period, from the Puritans through Melville, to determine how various writers understood their relationship to a new world of seemingly unlimited possibility. Authors covered may include Mary Rowlandson, Benjamin Franklin, Hannah Foster, Harriet Jacobs, Emerson, Thoreau, Harriet Beecher Stowe, Hawthorne, and Melville. Not offered 2009–10.

En 133. 19th-Century American Women Writers. *9 units (3-0-6), second term.* This course will analyze many of the most popular novels written in the 19th century. How might we account for their success in the 19th century and their marginalization (until recently) in the 20th century? Why were so many of these texts "sentimental"? How might we understand the appeal of "sentimental" literature? What are the ideological implications of sentimentalism? Authors may include Stowe, Warner, Cummins, Alcott, Phelps, Fern, etc. Instructor: Staff.

En 134. The Career of Herman Melville. *9 units (3-0-6), first term.* The course will focus on Melville's works from *Typee* through *Billy Budd*. Special emphasis will be placed on Melville's relations to 19th-century American culture. Instructor: Weinstein. Instructor: Staff.

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.* Instructor: Sutherland. Not offered in 2009–10.

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 2009–10.

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 2009–10.

En 141. James and Wharton. *9 units (3-0-6); third term.* The course covers selected novels, short fiction, and nonfiction writings of friends and expatriates Henry James and Edith Wharton. It will consider formal questions of style and genre as well as the literature's preoccupation with describing and defining American modernity, despite the authors' shared ambivalence toward their native country. Students will read as many as, but no more than, five novels. Texts covered may include *The Portrait of a Lady*, *Daisy Miller*, *The Ambassadors*, selections from *The Decoration of Houses*, *The House of Mirth*, *The Custom of the Country*, and *The Age of Innocence*. Not offered 2009–10.

En 145. American Ethnic Literature and the Drama of Assimilation. *9 units (3-0-6).* From the idea of the melting pot to contemporary debates about multiculturalism, ideas about assimilation have been crucial to understanding what it means to be American. As a nation of immigrants, the United States has produced countless narratives that describe the struggles of newcomers to adapt to an alien culture while they are also trying to negotiate a meaningful relation to their native culture. We will be reading novels, autobiographies, sociology, and other texts that address the meaning of assimilation and consider the costs, benefits, and the very possibility of joining the cultural mainstream. Not offered 2009–10.

En 148. Modern American Poetry. *9 units (3-0-6); first term.* A study of modern American poetry in its historical and literary context. Exploring some of the most innovative and difficult writing in the English language, this course confronts the startling range of poetic composition in the United States in the 20th century. Poets studied will include T. S. Eliot, Ezra Pound, Gertrude Stein, William Carlos Williams, Robert Frost, Wallace Stevens, Mina Loy, Marianne Moore, Langston Hughes and Allen Ginsberg among others. Instructor: Baskin.

En 150. Fundamentals of the Art of Poetry. *9 units (3-0-6); first term.* What is poetry? Why and how should one read it? What "weapons" does the good poem deploy in order to give pleasure? How does an inexperienced reader develop into an expert and a sensitive one? To illustrate the nature, functions, and resources of poetry, a wide-ranging selection of poems will be read and discussed. Instructor: Mandel.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6)*. This course introduces students to Hollywood films and filmmaking during the classical period, from the coming of sound through the '50s. It will cover basic techniques and vocabulary of film analysis, as we learn to think of films as texts with distinctive formal properties. Topics include the rise and collapse of the studio system, technical transformations (sound, color, deep focus), genre (the musical, the melodrama), cultural contexts (the Depression, World War II, the Cold War), audience responses, and the economic history of the film corporations. Terms may be taken independently. First quarter covers the period 1927–1940. Second quarter covers 1941–1960. Not offered 2009–10.

En 170. Drama from the Middle Ages to Molière. *9 units (3-0-6); third term.* A study of major dramatic works from the 15th to the mid-17th century. Students will read medieval plays like Abraham and Isaac and Everyman; British Renaissance works including Marlowe's Doctor Faustus and two Shakespearean plays; several Spanish comedias of the Golden Age, among them the original Don Juan play; and Molière's masterpieces: *Tartuffe* and *The Misanthrope*. Not offered 2009–10.

En 171. Drama from Molière to Wilde. *9 units (3-0-6), third term.* A study of French plays of the age of Louis XIV, featuring Molière and Racine; English comedies of the 17th and 18th centuries, including Sheridan's *The Rivals;* masterpieces of German drama of the Romantic age, among them Schiller's *Maria Stuart* and Goethe's *Faust; The Inspector General* by the Russian Nikolay Gogol; Edmond Rostand's *Cyrano de Bergerac;* Oscar Wilde's *The Importance of Being Earnest*, and other works as time permits. Instructor: Staff.

En 172. Drama from Ibsen to Beckett. *9 units (3-0-6); second term.* A wide international range of plays will be studied, beginning with major texts by Ibsen and Chekhov, and concluding with Ionesco and Beckett. In between, students will read important plays by G. B. Shaw, Sean O'Casey, Pirandello, Bertolt Brecht, T. S. Eliot, Arthur Miller, and others. Not offered 2009–10.

En 180. Special Topics in English. *9 units (3-0-6). See registrar's announcement for details.* Instructor: Staff.

En 181 a. Classics of Science Fiction: 1940–70. *9 units (3-0-6); third term.* This course will aim to examine, critically, the achievements of one of the many "golden ages" of science fiction. Among the authors examined will be Pohl and Kornbluth, Bradbury, Bester, Vonnegut, Wyndham, Heinlein, Dick, Herbert, Ballard, Le Guin, Asimov, Clarke, Silverberg, Aldiss. The course will aim to give formal and generic definition to the texts examined and to reinsert them into the period of their original publication. Not offered 2009–10.

En 181 b. Hardy: The Wessex Novels. *9 units (3-0-6); third term.* This course will examine the body of work that the late Victorian novelist Thomas Hardy published under the general title *The Wessex Novels*, that is, the sequence of works from *Far from the Madding Crowd* to *Jude the Obscure.* The six main novels will be read critically to give a sense of the totality of this greatest British regional novelist's achievement. Not offered 2009–10.

En 181 c. Classics of Science Fiction: The 1960s. *9 units (3-0-6); third term.* This course will aim to examine critically the achievements of one of the many "golden ages" of science fiction. Among the authors dealt with (but not necessarily restricted to) in the course will be Pohl and Kornbluth, Bester, Dick, Asimov, Clarke, Aldiss, Ballard, Le Guin, Wyndham. The course will aim to give formal and generic definition to the texts covered and to reinsert them into the period of their original conception and publication. Not offered 2009–10.

En 181 d. Jane Austen, Our Contemporary. *9 units (3-0-6); first term.* This course will examine in sequence, and in depth, the major novels of Jane Austen: *Northanger Abbey*, *Sense and Sensibility*, *Pride and Prejudice*, *Emma*, *Mansfield Park*, and *Persuasion*. In addition to intensive reading, attention will be given to the many adaptations of Austen's novels in other media. Instructor: Sutherland.

En 181 e. 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. Instructor: Staff.

ENGLISH AS A SECOND LANGUAGE

Please see pages 238–239 for requirements regarding English competency. All of the following courses are open to international graduate students only.

ESL 101 ab. Oral Communication and Pronunciation. *3 units (3-0-0); first and second terms.* Communication and pronunciation in spoken English. Development of pronunciation, vocabulary, listening comprehension, and accuracy and fluency in speaking. Aspects of American culture will be discussed. The first term is required for all first-year international students designated by the ESL screening process. Passing the class is based on attendance and effort. Graded pass/fail. Instructors: Geasland, Laib.

ESL 102. Advanced Spoken English for Academic Purposes. *Noncredit; first and third terms.* Development of fluency and communication strategies. Emphasis on presentation skills and interpersonal communication on scientific topics. Strongly recommended for first-time international graduate teaching assistants. Instructors: Geasland, Laib.

ESL 103. English in Everyday Life. *Noncredit; first, second, third terms.* Expressions, vocabulary, slang, and idioms used in daily life. Conversation and discussion, with feedback from instructors. Occasional grammar and pronunciation review. Comprehension of newspaper and magazine articles, as well as films and television programs. Instructors: Geasland, Laib.

ESL 104. Pronunciation Improvement and Accent Reduction. *Noncredit; second term.* Aspects of American English pronunciation. Vowels and consonants, word and syllable stress, sentence stress and rhythm, intonation, and linking. Intensive practice and techniques for achieving correct pronunciation through self-monitoring. Instructors: Geasland, Laib.

ESL 105. Oral Presentation and Public Speaking. *Noncredit; second, third terms.* Oral presentation in a variety of settings, including oral exams, seminars, conferences, and the classroom. Focus on the organization of ideas, delivery techniques, pronunciation, grammar, and vocabulary. Frequent in-class presentations by students based on their current research interests, followed by critiques. Improvement of confidence and delivery skills. Instructors: Geasland, Laib.

ESL 106. Writing Seminar. *Noncredit; third term.* Strategies for improving academic writing. Emphasis on grammar, word choice, organization, logical connectors, and punctuation. Classroom exercises and editing practice based on student writing samples. Instructors: Geasland, Laib.

ENVIRONMENTAL SCIENCE AND ENGINEERING

ESE 1. Introduction to Environmental Science and Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 1 ab, Ch 1 ab, and Ma 1 ab.* An introduction to the array of major scientific and engineering issues related to environmental quality on a local, regional, and global scale. Fundamental aspects of major environmental problems will be addressed with an overall focus on the dynamic interplay among the atmosphere, biosphere, geosphere, and hydrosphere. Underlying scientific principles based on biology, chemistry, and physics will be presented. Engineering solutions to major environmental problems will be explored. Not offered on a pass/fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Instructor: Leadbetter.

ESE 90. Undergraduate Laboratory Research in Environmental Science and Engineering. *Units by arrangement; any term. Approval of research supervisor required prior to registration.* Independent research on current environmental problems; laboratory or field work is required. A written report is required for each term of registration. Graded pass/fail. Instructor: Staff.

ESE 100. Special Topics in Environmental Science and Engineering. *6 or more units as arranged. Prerequisite: instructor's permission.* Special courses of reading, problems, or research for first-year graduate students or qualified undergraduates. Graded pass/fail. Instructor: Staff.

ESE 101. Current Problems in Environmental Science and Engineering. *3 units; first term.* A discussion course that focuses on current research by ESE faculty, and open research questions in the field. Required for first-year ESE graduate students. Instructor: Wennberg.

ACM/ESE 118. Methods in Applied Statistics and Data Analysis. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

ESE 142. Aquatic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 1 or instructor's permission.* Principles of inorganic and physical chemistry applied to natural and engineered aquatic systems. Biogeochemical processes controlling the major ion composition of aquatic systems and the behavior of the trace inorganic constituents of such systems are examined. Fundamental aspects of thermodynamics and quantitative description of the composition of natural waters are stressed. Instructor: Adkins.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

ESE 144. Applications of Aquatic Chemistry. *9 units (3-0-6); second term. Prerequisite: ESE 142.* Case studies are used to illustrate the effects of biogeochemical processes on the composition of ground and surface waters. Systems to be examined include natural waters subject to varying levels of perturbations as a result of human activities, and engineered systems, such as constructed wetlands or water treatment systems. Quantitative equilibrium and kinetic modeling are emphasized. Not offered 2009–10.

Ge/ESE 145. Isotopic Biogeochemistry Seminar. *6 units (3-0-3).* For course description, see Geological and Planetary Sciences.

ESE/Ge 148 abc. Global Environmental Science. *9 units each term. Prerequisites: Ch 1, Ma 2, Ph 2, or equivalents.* Global change on time-scales of years to centuries.

a. Climate Change. *(3-0-6); first term.* Radiative transfer and the greenhouse effect. Scattering and absorption by gases, clouds, and aerosols. Feedbacks due to water vapor, clouds, ice, and vegetation. Chemistry of greenhouse gases. Climates of the past. Ice ages. The global-warming debate. Economic and political aspects of climate change. Instructor: Wennberg.

b. Atmosphere-Ocean Circulations. *(3-0-6); second term.* Large-scale motions in Earth's atmosphere and oceans. Effects of planetary rotation and density stratification. Observing systems and data assimilation. Numerical weather prediction. Climate modeling. Parameterizations. Dynamical aspects of El Niño, global warming, and the ozone hole. Instructor: Bordoni.

c. Biogeochemical Cycles. *(3-0-6); third term.* Global biogeochemical cycles, fluxes, and reservoirs in the solid earth, oceans, biosphere, and atmosphere. The hydrologic cycle, weathering and erosion, soil formation, nutrient cycling and limitation, ecosystem function and metrics, photosynthesis and primary production, heterotropic recycling, carbon cycle dynamics, atmospheric trace gases, and stable-isotope tracers. Variability in biogeochemical cycles over Earth history, and recent modification by human activities. Instructor: Sessions.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ESE 150 abc. Seminar in Environmental Science and Engineering. *1 unit; each term.* Seminar on current developments and research within the field of environmental engineering science, with special consideration given to work at the Institute. Graded pass/fail. Instructor: Wennberg.

ESE/Ge 152. Atmospheric Radiation. *9 units (3-0-6); third term. Prerequisite: ESE/Ge 148 a or instructor's permission.* The basic physics of absorption and scattering by molecules, aerosols, and clouds. Theory of radiative transfer. Band models and correlated-k distributions and scattering by cloud and aerosol particles. Solar insolation, thermal emission, heating rates, and applications to climate and remote sensing. Instructor: Yung.

ESE/Ge 153. Atmosphere and Ocean Dynamics. *9 units (3-0-6); second term. Prerequisite: ESE 148 b or an introductory fluid dynamics course.* Fluid dynamics of the atmosphere and oceans, beginning with linear wave dynamics and leading to theories of the maintenance of large-scale circulations. Topics include barotropic Rossby waves, flow-over topography; shallow-water dynamics and potential vorticity; quasi-geostrophic theory; barotropic and baroclinic instability; wave–mean flow interaction; maintenance of the global-scale circulation of the atmosphere; structure of wind-driven ocean circulation. Instructor: Schneider.

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.

ChE/ESE 158. Aerosol Physics and Chemistry. *9 units (3-0-6).* For course description, see Chemical Engineering.

ESE 159. Environmental Analysis Laboratory. *9 units (1-6-2); third term. Prerequisite: any 100-level ESE course or instructor's permission.* Introduction to modern laboratory techniques and basic sampling principles in environmental water, air, and biological analysis. Modular experiments will address sampling, measurement, and data analysis based around a region of local environmental interest. Regions may include the Arroyo Seco watershed, San Gabriel Mountains, or Caltech campus. Principles of basic experimental design, laboratory technique, elementary statistics, and scientific writing will be emphasized. Instructors: Leadbetter, Flagan. Not offered 2009–10.

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. Not offered 2009–10.

Ge/ESE 170. 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- and aerosol-phase chemistry of the stratosphere and troposphere; sources, sinks, and lifetimes of trace atmospheric species; stratospheric ozone chemistry; oxidation mechanisms in the troposphere. Instructors: Seinfeld, Wennberg.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0); first term. Prerequisite: ESE/Ge/Ch 171 or equivalent.* A lecture and discussion course about active research in atmospheric chemistry. Potential topics include halogen chemistry of the stratosphere and troposphere; aerosol formation in remote environments; coupling of dynamics and photochemistry; development and use of modern remote-sensing and in situ instrumentation. Graded pass/fail. Instructors: Seinfeld, Wennberg.

ESE/Ge 173. Topics in Atmosphere and Ocean Dynamics. *9 units (3-0-6); first term. Prerequisite: ESE/Ge 153 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 geostrophic turbulence, atmospheric convection and cloud dynamics, wave dynamics and large-scale circulations in the tropics, middle-atmosphere dynamics, dynamics of El Niño and the southern oscillation, maintenance of the ocean thermocline, and dynamics of the southern ocean. Instructor: Schneider.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6); second, third terms.* A detailed analysis of the important chemical reactions and physicochemical processes governing the behavior and fate of organic compounds in the surface and subsurface aquatic environments. The course is focused on physical organic chemistry relevant to natural waters. Fundamental aspects of thermodynamics, kinetics, mechanisms, and transport are stressed. Instructor: Hoffmann.

ESE 200. Advanced Topics in Environmental Science and Engineering. *Units by arrangement, any term.* Course to explore new approaches to environmental problems. The topics covered vary from year to year, depending on the interests of the students and staff.

ESE 250. Advanced Environmental Seminar. *Units by arrangement, not to exceed 4 units (2-0-2); each term. Prerequisite: instructor's permission.* A seminar course for advanced graduate students and staff to discuss current research and technical literature on environmental problems. As the subject matter changes from term to term, it may be taken any number of times. Not offered 2009–10.

ESE 300. Thesis Research.

For other closely related courses see listings under Chemistry, Chemical Engineering, Civil Engineering, Mechanical Engineering, Biology, Geology, Economics, and Social Science.

Graduate students may also enroll in graduate courses offered by the Scripps Institution of Oceanography under an exchange program. Graduate students majoring in environmental science and engineering, who may take a subject minor in oceanography for the Ph.D. degree, should consult the executive officer for more information.

FILM

F/En 30. Introduction to Film. *9 units (3-0-6).* This course examines film as an art and as an institution from 1895 through the present. Students will acquire the basic vocabulary and techniques of film analysis, focusing on questions of form (mise-en-scène, cinematography, editing, sound) and narrative, as well as an understanding of the historical development of the medium with an emphasis on the American, European, and Asian contexts. Topics will include the early cinema of illusion, the actuality film, the transition to sound, the Hollywood star system, Italian neorealism, the French New Wave, Dogma 95, and Hong Kong action cinema. Not offered 2009–10.

F/Hum 32. Humanities on Film. *3 units (1-1-1); offered by announcement.* A course centered around a series of films (usually five) screened as part of the Caltech film program. Students will be required to attend prefilm lectures and postfilm discussions, to do some reading, and to produce a short paper.

L/F 104. French Cinema. *9 units (3-0-6).* For course description, see Languages.

H/F 131. History on Film. *9 units (2-2-5).* For course description, see History.

H/F 133. Topics in Film History. *9 units (2-2-5).* For course description, see History.

H/F 134. The Science Fiction Film. *9 units (2-2-5).* For course description, see History.

H/F 136. Ethnic Visions. *9 units (2-2-5).* For course description, see History.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6).* For course description, see English.

GEOLOGICAL AND PLANETARY SCIENCES

Geology, Geobiology, Geochemistry, Geophysics, Planetary Science

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Ge 1. Earth and Environment. *9 units (3-3-3); third term.* An introduction to the ideas and approaches of earth and environmental sciences, including both the special challenges and viewpoints of these kinds of science as well as the ways in which basic physics, chemistry, and biology relate to them. In addition to a wide-ranging lecture-oriented component, there will be a required field trip component (two weekend days). The lectures and topics cover such issues as solid earth structure and evolution, plate tectonics, oceans and atmospheres, climate change, and the relationship between geological and biological evolution. Not offered on a pass/fail basis. Instructor: Wernicke. *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. Instructors: Farley, Clayton.

Ge 11 abcd. Introduction to Earth and Planetary Sciences. *9 units each term.* Comprehensive, integrated overview of Earth and planets. Although designed as a sequence, any one term can be taken as a stand-alone course. Biologists are particularly welcome in Ge 11 b, as are physicists and astronomers in Ge/Ay 11 c.

a. Earth as a Planet. *(3-3-3); first term.* Systematic introduction to the physical and chemical processes that have shaped Earth as a planet over geological time, and the observable products of these processes—rock materials, minerals, land forms. Geophysics of Earth. Plate tectonics; earthquakes; igneous activity. Metamorphism and metamorphic rocks. Rock deformation and mountain building. Weathering, erosion, and sedimentary rocks. Evolution of land forms in response to wind, water, ice, and tectonic processes. The causes and recent history of climate change. The course includes one three-day field trip and a weekly laboratory section focused on the identification of rocks and minerals and the interpretation of topographic and geological maps. Instructor: Eiler.

b. Earth and the Biosphere. *(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. Instructors: Fischer, Kirschvink.

Ge/Ay 11 c. Planetary Sciences. *(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 dynamics and chemical processes. Instructor: Ingersoll.

d. 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. Instructors: Clayton, Gurnis, Jackson.

Ge 13. Scientific Writing Tutorial in the Geological and Planetary Sciences. *3 units (1-0-2); third term.* This class provides the opportunity for students to gain experience in writing a substantial paper in the style typical of peer-reviewed journals, such as *Annual Reviews of Earth and Planetary Sciences*, *Geology*, *Science*, or *Nature*. Grading will be evaluated jointly by each student's adviser and the course instructor. *Fulfills the Institute scientific writing requirement.* Instructors: Kirschvink, staff.

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 100 abc. Geology Club. *1 unit; first, second, third terms.* Presentation of papers on research in geological and planetary sciences by guest speakers. Graded pass/fail. Instructor: Kirschvink.

Ge 101. Introduction to Geology and Geochemistry. *12 units (4-0-8); first term. Prerequisite: graduate standing or instructor's permission.* A broad, high-level survey of geology and geochemistry with emphasis on quantitative understanding. Historical deduction in the geological and planetary sciences. Plate tectonics as a unifying theory of geology. Igneous and metamorphic processes, structural geology and geomorphology; weathering and sedimentary processes. Nucleosynthesis and chemical history of the solar system; distribution of the elements in the earth; isotopic systems as tracers and clocks; evolution of the biosphere; global geochemical and biogeochemical cycles; geochemical constraints on deep Earth structure. One mandatory three-day field trip, selected laboratory exercises, and problem sets. Instructor: Asimow.

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. Instructor: Simons.

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: Ingersoll.

Ge 104. Introduction to Geobiology. *9 units (3-1-5); first term. Prerequisite: instructor's permission.* Lectures about the coevolution of life and Earth. Basic concepts in geology and biology are presented in the context of significant events in Earth's history. The course provides a brief introduction to essential concepts in biology and geology to provide a common foundation for all students. Important geobiological processes and major events are discussed, including fossilization, the earliest records of life, evolution of photosynthesis and the oxygenation of Earth's environment, origin of animals at the Precambrian-Cambrian boundary, extinction of invertebrates at the Permian-Triassic boundary, and the Eocene-Paleocene thermal crisis. A weekend field trip to modern and ancient geobiological sites. Instructors: Grotzinger, Orphan.

Ge 106. Introduction to Structural Geology. *9 units (3-0-6); third 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. *3 units (1-0-2); third term.* Practice in the effective organization and delivery of reports before groups. Successful completion of this course is required of all candidates for degrees in the division. Graded pass/fail. Instructors: Bikle, 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). Instructor: Avouac.

Ge 111 ab. Applied Geophysics Seminar and Field Course. 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.

a. Applied Geophysics Seminar. *6 units (3-3-0); second term. Prerequisite: instructor's permission.*

b. Applied Geophysics Field Course. *9 units (0-3-6); spring break, third term. Prerequisite: Ge 111 a.*

Ge 112. Sedimentology and Stratigraphy. *12 units (3-5-4); first term. Prerequisite: Ge 11 ab.* Systematic analysis of transport and deposition in sedimentary environments and the resulting composition, texture, and structure of both clastic and chemical sedimentary rocks. The nature and genesis of sequence architecture of sedimentary basins and cyclic aspects of sedimentary accumulation will be introduced. Covers the formal and practical principles of definition of stratigraphic units, correlation, and the construction of a geologic timescale. Field trip and laboratory exercises. Instructor: Myrow.

Ge 114 ab. Mineralogy.

a. *9 units (3-4-2); first term.* Atomic structure, composition, physical properties, occurrence, and identifying characteristics of the major mineral groups. The laboratory work involves the characterization and identification of important minerals by their physical and optical properties. Instructor: Rossman.

b. *3 units (0-2-1); first term. Prerequisite: concurrent enrollment in Ge 114 a or instructor's permission.* Additional laboratory studies of optical crystallography and the use of the petrographic microscope. Instructor: Rossman.

Ge 115 abc. Petrology and Petrography. Study of the origin and evolution of igneous and metamorphic rocks with emphasis on use of phase equilibria, microscopic petrography, and geochemistry.

a. Igneous Petrology. *6 units (3-0-3); second term. Prerequisite: Ge 114 ab.* The origin, occurrence, and classification of igneous rocks, considered mainly in the light of phase equilibria and geochemistry. Instructor: Stolper.

b. Metamorphic Petrology. *6 units (3-0-3); third term. Prerequisite: Ge 115 a.* 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. Instructor: Eiler.

c. Petrography Laboratory. *6 units (0-4-2); third term. Prerequisites: Ge 115 a and concurrent enrollment in Ge 115 b.* Laboratory exercise dealing with examination of igneous and metamorphic rocks in hand-sample and with the petrographic microscope. Instructor: Staff.

Ge 116. Analytical Techniques Laboratory. *6 units (1-4-1); second term.* 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 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, Farley.

Ge 120 ab. Field Geology. A comprehensive introduction to methods of geological field mapping through laboratory exercises followed by summer field camp. Instructor: Saleeby.

a. Introduction to Field Geology. *6 units (1-5-0); third term. Prerequisite: Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106).*

Laboratory exercises introduce geometrical and graphical techniques in the analysis of geologic maps. Field trips introduce methods of geological mapping. Given in alternate years; offered 2009–10.

b. Summer field camp. *18 units (0-18-0); summer. Prerequisite: Ge 120 a or instructor's permission.* Intensive three-week field course in a well-exposed area of the southwestern United States covering techniques of geologic field observation, documentation, and analysis. Field work begins immediately following Commencement Day in June. Given in alternate years; offered summer 2010.

Ge 121 ab. Advanced Field and Structural Geology. *12 units (0-9-3); first, second terms. Prerequisite: Ge 120 or equivalent, or instructor's permission.* Field mapping and supporting laboratory studies in topical problems related to the geology of the southwestern U.S. Course provides a breadth of experience in igneous, metamorphic, and sedimentary rocks. Either 121 a or 121 b may be taken more than once for credit. Instructors: Stock (first term), Grotzinger (second term).

Ge 124 ab. Paleomagnetism and Magnetostratigraphy. Application of paleomagnetism to the solution of problems in stratigraphic correlation and to the construction of a high-precision geological timescale. Instructor: Kirschvink. Given in alternate years; not offered 2009–10.

a. *6 units (0-0-6); third term.* A field trip to the southwest United States or Mexico to study the physical stratigraphy and magnetic zonation, followed by lab analysis.

b. *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.

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 2009–10.

Ge 126. Topics in Earth Surface Processes. *6 units (2-0-4); second term.* A seminar-style course focusing on a specific theme within geomorphology and sedimentology depending on student interest. Potential themes could include river response to climate change, bedrock erosion in tectonically active mountain belts, or delta evolution on Earth and Mars. The course will consist of student-led discussions centered on readings from peer-reviewed literature. Instructor: Lamb.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6); second 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 2009–10.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); third term. Prerequisite: 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. 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. Not offered 2009–10.

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); second 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 2009–10.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6); first term.* Review current theoretical ideas and observations pertaining to the formation and evolution of planetary systems. Topics to be covered include low-mass star formation, the protoplanetary disk, accretion and condensation in the solar nebula, the formation of gas giants, meteorites, the outer solar system, giant impacts, extrasolar planetary systems. Instructors: Blake, Brown.

Ge 135. Ophiolite Emplacement and Forearc Structure of Central California. *5 units (1-4-0). Prerequisite: instructor's permission.* Intensive preparation and follow-up lecture/laboratory sessions focusing on field observations of western Sierra Nevada ophiolite belt and Great Valley forearc basin structure. Instructor: Saleeby. Given in alternate years; offered 2009–10.

Ge 136 abc. Regional Field Geology of the Southwestern United States. *3 units (1-0-2); first, second, or third terms, by announcement. Prerequisite: Ge 11 ab or Ge 101, or instructor's permission.* Includes approximately three days of weekend field trips into areas displaying highly varied geology. Each student is assigned the major responsibility of being the resident expert on a pertinent subject for each trip. Graded pass/fail. Instructor: Kirschvink.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6); first term. Prerequisites: Ph 106 abc, ACM 95/100 abc.* Solar-system dynamics, with emphasis on slow changes in the orbit and rotation rates of planets and satellites. Topics: tidal friction, resonant orbits and rotation rates, gravitational fields of planets and satellites, dynamics of polar wandering, continental drift, and planetary rings. Given in alternate years; not offered 2009–10.

Ge 140. Introduction to Isotope Geochemistry. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* An introduction to the physics and chemistry of isotopes and a broad overview of the principles and conceptual techniques used in the stable isotope geochemistry of the lighter elements (H, C, O, N, Si, S) and the origin and evolution of radiogenic parent-daughter systems in nature. Instructors: Eiler, Farley.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4); first term. Prerequisite: Ch 41 a or equivalent.* Main topics include the analysis, properties, sources, and cycling of natural organic materials in the environment, from their production in living organisms to burial and decomposition in sediments and preservation in the rock record. Specific topics include analytical methods for organic geochemistry, lipid structure and biochemistry, composition of organic matter, factors controlling organic preservation, organic climate and 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 Fm. Instructor: Sessions. Given in alternate years; not offered 2009–10.

Ge/ESE 145. Isotopic Biogeochemistry Seminar. *6 units (3-0-3); first term. Prerequisite: Ge 140 or instructor's permission.* Advanced seminar to discuss research and papers in stable isotope biogeochemistry and geobiology. Topics will vary from year to year, and may be taken multiple times for credit. Instructor: Sessions. Given in alternate years; offered 2009–10.

Ge 147. Tectonics of Western North America. *9 units (4-0-5); first term. Prerequisite: Ge 11 ab.* Major tectonic features of western North America, including adjacent craton and Pacific Ocean basin. Active plate junctures, igneous provinces, crustal uplift, and basin subsidence. Tectonic evolution from late Precambrian to recent time, and modern analogues for paleotectonic phenomena. In some years, course will focus specifically on the Southern California region basement and its disruption by Neogene to recent tectonics, with three one-day weekend local field trips spaced throughout the term. Alternates with Ge 135. Instructor: Saleeby. Given in alternate years; not offered 2009–10.

ESE/Ge 148 abc. Global Environmental Science. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6); third term.* 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; not offered 2009–10.

Ge 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. Fundamentals of Planetary Surfaces. *9 units (3-3-3); third term.* Review of surface histories and processes responsible for the formation and modification of the surfaces of the terrestrial planets and the Jovian satellites. Topics: exogenic surface processes, including impact, gravitational degradation, atmospheric modification of surfaces by wind and water, and the direct interaction of surfaces with plasmas; endogenic modification of surfaces by tectonics and volcanism; surface histories of Mercury, Venus, the moon, and Mars; the surfaces of icy bodies. Instructor: Aharonson.

ESE/Ge 152. Atmospheric Radiation. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge 153. Atmosphere and Ocean Dynamics. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

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.

Ge/ESE 155. Paleoceanography. *9 units (3-0-6); third term.* Evaluation of the data and models that make up our current understanding of past climates. Emphasis will be placed on a historical introduction to the study of the past ten thousand to a few hundred thousand years, with some consideration of longer timescales. Evidence from marine and terrestrial sediments, ice cores, corals, and speleothems will be used to address the mechanisms behind natural climate variability. Models of this variability will be evaluated in light of the data. Topics will include sea level and ice volume, surface temperature evolution, atmospheric composition, deep ocean circulation, tropical climate, ENSO variability, and terrestrial/ocean linkages. Instructor: Adkins. Given in alternate years; offered 2009–10.

Ge 156. Topics in Planetary Surfaces. *6 units (3-0-3); second term.* 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. Instructor: Aharonson.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6); second term.* Photochemistry of planetary atmospheres, comparative planetology, atmospheric evolution. What makes Earth habitable? Remote sensing of extrasolar planets, biosignatures. Instructor: Yung. Given in alternate years; not offered 2009–10.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aerospace.

Ge 161. Plate Tectonics. *9 units (3-0-6); first term. Prerequisite: Ge 11 ab or equivalent.* Geophysical and geological observations related to plate tectonic theory. Instantaneous and finite motion of rigid plates on a sphere; marine magnetic and paleomagnetic measurements; seismicity and tectonics of plate boundaries; reference frames and absolute plate motions. Interpretations of geologic data in the context of plate tectonics; plate tectonic evolution of the ocean basins. Instructor: Stock.

Ge 162. Seismology. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 abc 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: Heaton.

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 of Earth's Interior. *9 units (3-0-6); second term. Prerequisites: Ch 1 ab, Ph 1 ab, Ma 1 ab.* This course will introduce and explore the mineral physics of Earth's interior. Topics to be covered: elasticity and equations of state, vibrational and electronic properties of minerals, transport properties, phase transitions; determinations of pressure and temperature of samples under extreme conditions; application of mineral physics data to Earth and planetary interiors. A short survey will be given on experimental approaches used in mineral physics, with an emphasis on recent advances in synchrotron-based X-ray scattering methods at extreme conditions. Instructor: Jackson. Given in alternate years; offered 2009–10.

Ge 165. Geophysical Data Analysis. *9 units (3-0-6); first term. Prerequisites: basic linear algebra and Fourier transforms.* Introduction to modern digital analysis: discrete Fourier transforms, Z-transforms, filters, deconvolution, auto-regressive models, spectral estimation, basic statistics, 1-D wavelets, model fitting via singular valued decomposition. Instructor: Clayton.

Ge 167. Tectonic Geodesy. *9 units (3-0-6); third term.* 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.

Ge 168. Crustal Geophysics. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 or equivalent, or instructor's permission.* The analysis of geophysical data related to crust processes. Topics include reflection and refraction seismology, tomography, receiver functions, surface waves, and gravity. Instructor: Clayton.

Ge 169 abc. Readings in Geophysics. *6 units (3-0-3); first, second, third terms.* Reading courses are offered to teach students to read critically the work of others and to broaden their knowledge about specific topics. Each student will be required to write a short summary of each paper that summarizes the main goals of the paper, to give an assessment of how well the author achieved those goals, and to point out related issues not discussed in the paper. Each student will be expected to lead the discussion on one or more papers. The leader will summarize the discussion on the paper(s) in writing. A list of topics offered each year will be posted on the Web. Individual terms may be taken for credit multiple times without regard to sequence. Instructor: Staff.

Ge/ESE 170. Microbial Ecology. *9 units (3-2-4); third term. Prerequisite: ESE/Bi 166.* 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. Instructor: Orphan.

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.

ESE/Ge 173. Topics in Atmosphere and Ocean Dynamics. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge 174. Geobiological Constraints on Earth History. *9 units (3-1-5); second term. Prerequisite: instructor's permission.* Systematic analysis of the origin and evolution of life in the solar system as read through the geological record. Effects of global glaciations, volcanism, and impact processes on the atmosphere, hydrosphere, and climate of Earth. Magnetofossils, genes as fossils, banded iron stones, algal mats, stromatolites, global glaciation, mass extinction events, the Cambrian Explosion, human and molecular evolution. The course usually includes one or two major field trips, in which each student is assigned the responsibility of being the resident expert on a pertinent subject for each trip. Instructor: Kirschvink.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge 177. Active Tectonics. *12 units (3-3-6); second 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. Given in alternate years; offered 2009–10.

Ge 179 abc. Seismological Laboratory Seminar. *1 unit; first, second, third terms.* Presentation of current research in geophysics by students, staff, and visitors. Graded pass/fail. Instructor: Helmberger.

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. Instructor: Staff.

Ge 192. Special Topics in the Geological Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the geological sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 193. Special Topics in Geophysics. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in geophysics. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 194. Special Topics in the Planetary Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the planetary sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 195. Special Opportunities in Field Geology. *Units to be arranged. Offered by announcement only.* 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 211. Applied Geophysics II. *Units to be arranged. Prerequisite: instructor's permission.* Intensive geophysical field experience in either marine or continental settings. Marine option will include participation in a student training cruise, with several weeks aboard a geophysical research vessel, conducting geophysical measurements (multibeam bathymetry, gravity, magnetics, and seismics), and processing and interpreting the data. Supporting lectures and problem sets on the theoretical basis of the relevant geophysical techniques and the tectonic background of the survey area will occur before and during the training cruise. The course might be offered in a similar format in other isolated situations. The course will be scheduled only when opportunities arise and this usually means that only six months' notice can be given. Auditing not permitted. Class may be taken more than once. Instructors: Stock, Clayton, Gurnis.

Ge 212. Thermodynamics of Geological Systems. *9 units (3-0-6); third 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 nonideal 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; not offered 2009–10.

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 2009–10.

Ge 215. Topics in Advanced Petrology. *12 units (4-0-8); third 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; offered 2009–10.

Ge 225 abc. Planetary Sciences Seminar. *1 unit; first, second, third terms.* Required of all planetary-science graduate students; others welcome. First term: current research by staff and students. Second and third terms: planetary research with spacecraft and current developments in planetary science. Instructor: Staff.

Ge 232. Chemistry of the Solar System. *9 units (3-0-6); second term. Prerequisite: Ge 140 or instructor's permission.* Advanced course using both chemical and isotopic data to evaluate the current state of knowledge concerning the composition of major segments of the solar system, viz., solar and meteoritic abundance data to infer the average solar-system composition; chemistry of meteorites as a clue to initial conditions in the solar nebula; bulk composition of the earth and moon; constraints on the bulk composition of the other planets, emphasizing data on atmospheric constituents. Instructor: Burnett. Given in alternate years; not offered 2009–10.

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 246. Molecular Geobiology Seminar. *6 units (2-0-4); second term. Recommended preparation: ESE/Bi 166.* Critical reviews and discussion of classic papers and current research in microbiology and geomicrobiology. As the topics will vary from year to year, it may be taken multiple times. Instructor: Orphan. Given in alternate years; offered 2009–10.

Ge 261. Advanced Seismology. *9 units (3-0-6); third term.* Continuation of Ge 162 with special emphasis on particular complex problems;

includes generalizations of analytical methods to handle nonplanar structures and methods of interfacing numerical-analytical codes in two and three dimensions; construction of Earth models using tomographic methods and synthetics. Requires a class project. Instructor: Helmberger.

Ge 263. Computational Geophysics. *9 units (3-0-6); second term. Prerequisites: introductory class in geophysics, class in partial differential equations, some programming experience.* Finite-difference, pseudospectral, 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, Ampuero. Given in alternate years; not offered 2009–10.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Aerospace.

Ge 268. Mantle Dynamics. *9 units (3-0-6); first term. Prerequisites: Ge 163 and Ge 263.* Analysis of mantle dynamics and connection with surface processes, especially plate tectonics. Selected problems will be examined, including the mechanics of subduction, mantle plumes, mantle convection, convective mixing, thermal evolution, and interpretation of seismic tomography. Term project using numerical models required. Instructor: Gurnis. Given in alternate years; offered 2009–10.

Ge 270. Continental Tectonics. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 or ACM 113; Ge 11 ab, Ge 106, Ge 162, or Ge 161.* The nature of nonplate, finite deformation processes in the evolution of the continental lithosphere, using the Alpine orogen as an example. Rheological stratification; isostatic and flexural response to near-vertical loads; rifting and associated basin development; collision and strike-slip tectonics; deep crustal processes. Instructor: Wernicke. Given in alternate years; offered 2009–10.

Ge 277. Active Tectonics Seminar. *6 units (2-0-4); second term.* Discussion of key issues in active tectonics based on a review of the literature. The topic of the seminar is adjusted every year based on students' interest and recent literature. Instructor: Avouac.

Ge 282 abc. Division Seminar. *1 unit; first, second, third terms.* Presentation of papers by invited investigators. Graded pass/fail.

Ge 297. Advanced Study. *Units to be arranged.*

Ge 299. Thesis Research. Original investigation, designed to give training in methods of research, to serve as theses for higher degrees, and to yield contributions to scientific knowledge.

HISTORY

Hum/H 1 ab. East Asian History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 2. American History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3 abc. European Civilization. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 4 abc. Civilization, Science, and Archaeology. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

H 40. Reading in History. *Units to be determined for the individual by the division. Elective, in any term.* Reading in history and related subjects, done either in connection with the regular courses or independently, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

H 98. Reading in History. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history, in areas not covered by regular courses. Instructor: Staff.

H 99 abc. Research Tutorial. *9 units (1-0-8). Prerequisite: instructor's permission.* Students will work with the instructor in the preparation of a research paper, which will form the basis of an oral examination. Instructor: Staff.

H 108 a. The Early Middle Ages. *9 units (3-0-6); second term.* This course is designed to introduce students to the formative period of Western medieval history, roughly from the fourth through the tenth centuries. It will emphasize the development of a new civilization from the fusion of Roman, Germanic, and Christian traditions, with a focus on the Frankish world. The course focuses on the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 108 b. The High Middle Ages. *9 units (3-0-6); third term.* This course is designed to introduce students to European history between 1000 and 1400. It will provide a topical as well as chronological examination of the economic, social, political, and religious evolution of western Europe during this period, with a focus on France, Italy, England, and Germany. The course emphasizes the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 109. Medieval Knighthood. *9 units (3-0-6); second 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 2009–10.

H 110. Saints, Sinners, and Sexuality in the Medieval World. *9 units (3-0-6); third term.* This course will investigate medieval conceptions of sanctity, transgression, and appropriate behavior for men and women. We will examine institutions as well as individuals, and explore real situations as well as the imaginary realms created in romances and manuscript marginalia. From the earliest Christian martyrs to Joan of Arc, we will investigate a wide range of sources—literary, artistic, and documentary—to get at the often contradictory but always fascinating intersections of faith, gender, and the forbidden in the medieval world. Instructor: Clark.

H 111. The Medieval Church. *9 units (3-0-6); offered by announcement.* This course takes students through the history of the medieval Christian Church in Europe, from its roots in Roman Palestine, through the zenith of its power in the high Middle Ages, to its decline on the eve of the Reformation. The course focuses on the church less as a religion (although it will by necessity deal with some basic theology) than as an institution that came to have an enormous political, social, cultural, and economic impact on medieval life, and for a brief time made Rome once more the mistress of Europe. Not offered 2009–10.

H 112. The Vikings. *9 units (3-0-6); third term.* This course will take on the Scandinavian seafaring warriors of the 8th–11th centuries as a historical problem. What were the Vikings, where did they come from, and how they did they differ from the Scandinavian and north German pirates and raiders who preceded them? Were they really the horned-helmeted, bloodthirsty barbarians depicted by modern popular media and by many medieval chronicles? What effect did they have in their roughly two centuries of raiding and colonization on the civilizations of medieval and ultimately modern Europe? Not offered 2009–10.

H 115 abc. British History. *9 units (3-0-6); first, second, third terms.* The political and cultural development of Great Britain from the early modern period to the 20th 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. Instructor: Staff.

H 116. Studies in Narrative: History, Fiction, and Storytelling. *9 units (3-0-6); second term.* This course examines the fraught relationship between historical and literary narratives, two interdependent but often opposed forms of storytelling. It will look at works that raise the issue of veracity and storytelling, including fictions like Graham Swift's *Waterland*, films such as Kurosawa's *Rashomon*, and the "historical novellas" in Simon Schama's book *Dead Certainties*. It will also investigate in some detail the works of American, French, and Italian historians who have tried to solve this problem by turning to so-called microhistory. Instructor: Brewer. Not offered 2009–10.

H 118. Histories of Collecting. *9 units (3-0-6); third term.* This course examines the history and theory of collecting, concentrating on collectors, collections, and collecting in the West since the Renaissance. It will include field trips to collections around Los Angeles, including the Huntington Art Gallery and the Museum of Jurassic Technology, and the examination of issues such as forgery and the workings of art markets. Instructor: Brewer.

H 119. Art Worlds. *9 units (3-0-6).* Among theorists and practitioners of art, the "art world" has come to be seen as a central force in the production of contemporary art. But what is the art world? When and how did it come to assume this remarkable importance? Drawing on resources including social history, philosophical aesthetics, artists' writings and anthropological theory, this course will examine crucial moments in the formation and changing conception of the art world. Topics include the relation of art worlds to the valuation, collecting, and market for art; the ambivalent relations of the art world to artistic avant-gardes; and the comparative strength of the art world's position in the age of 21st-century globalization. Objects from local collections, and local collections themselves, will be central to the analysis. The course will include a number of field trips as well as presentations by contemporary artists. Instructors: Brewer, Hunter.

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 antiglobalization movements of today. Not offered 2009–10.

H 122. Household and Family Forms over Time. *9 units (3-0-6); offered by announcement.* This course examines the wide variety of family forms and household structures in past societies, as well as the social, cultural, institutional, and economic variables that influenced them. The course focuses mainly on Europe from about 1600 to the present, as this is the area for which most research has been done, but there will be some discussion of other parts of the world, including Asia, Africa, and North and South America. Special attention is given to comparisons among different societies. Not offered 2009–10.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6).* 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. Instructor: Dennison.

H 130. Postmodern History. *9 units (3-0-6); offered by announcement.* 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 2009–10.

H/F 131. History on Film. *9 units (2-2-5); third term.* An investigation into the variety of ways history has been and can be represented on the screen. Some terms the focus will be a specific historical period or nation; other terms the focus will be the nature of film as a medium for history and biography. The class will include weekly screenings of films as well as weekly discussion sections. Instructor: Rosenstone.

H/F 133. Topics in Film History. *9 units (2-2-5); offered by announcement.* The course will focus each term on one kind of motion picture—either a film genre, or films made by an individual director, or from a single nation or region of the world or particular historical era. Included are weekly screenings, readings on film, a weekly discussion meeting, and a term paper. Instructor: Rosenstone.

H/F 134. The Science Fiction Film. *9 units (2-2-5); third term.* This course will introduce students to some of the classic works of the science fiction film from the earliest days of cinema until the present. It will analyze aesthetic, historical, and social documents, and will show that such films, while describing alternative, hypothetical, and futurist worlds, also serve as a commentary upon and/or a critique of contemporary (to the film) historical, social, political, and ideological systems and attitudes. Instructor: Rosenstone.

H 135. War, Conquest, and Empires. *9 units (3-0-6); offered by announcement.* 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. Not offered 2009–10.

H/F 136. Ethnic Visions. *9 units (2-2-5); offered by announcement.* In recent decades, directors from ethnic minorities that are often un- or misrepresented in mainstream Hollywood films have been making dramatic features depicting the history, problems, and prospects of their own communities. This course will feature a selection of such films by directors from African, Latino, Asian, Muslim, and European American ethnic groups, with an eye toward assessing the similarities and differences in the processes of immigration, acculturation, and Americanization. Not offered 2009–10.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6), second term.* The Russian intelligentsia registered the arrival of modern urban society with a highly articulate sensitivity, perhaps because these changes—industrialization, the breakdown of traditional hierarchies and social bonds, the questioning of traditional beliefs—came to Russia so suddenly. This gives their writings a paradigmatic quality; the modern dilemmas that still haunt us are made so eloquently explicit in them that they have served as models for succeeding generations of writers and social critics. This course explores these writings (in English translation) against the background of Russian society, focusing especially on particular works of Chekhov, Dostoevsky, Goncharov, Tolstoy, and Turgenev. Instructor: Dennison.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6).* For course description, see Art History.

HPS/H 156. The History of Modern Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 161. Selected Topics in History. *9 units (3-0-6)*; offered by announcement. Instructors: Staff, visiting lecturers.

HPS/H 162. Social Studies of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 167. Experimenting with History/Historic Experiment. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 172. History of Mathematics: A Global View with Close-ups. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 175. Matter, Motion, and Force: Physical Astronomy from Ptolemy to Newton. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 179. Cambridge Scientific Minds: How We See Them; How They See Themselves. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 182. Show and Tell: 3-D Models for the Visualization of Complex Concepts in the 16th and 17th centuries. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 201. Reading and Research for Graduate Students. *Units to be determined for the individual by the division.*

HISTORY AND PHILOSOPHY OF SCIENCE

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

HPS 98. Reading in History and Philosophy of Science. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history and philosophy of science, in areas not covered by regular courses. Instructor: Staff.

HPS 102 ab. Senior Research Seminar. *12 units (2-0-10). Offered in any two consecutive terms, by arrangement with HPS faculty.* Under the guidance of an HPS faculty member, students will research and write a focused research paper of 15,000 words (approximately 50 pages). Work in the first term will comprise intensive reading in the relevant literature and/or archival or other primary source research. In the second term, students will draft and revise their paper. Open to seniors in the HPS option and to others by special permission of an HPS faculty member. Instructor: Staff.

HPS 103. Public Lecture Series. *1 unit; first, second, third terms.* Student attend four lectures, featuring speakers from outside Caltech, on topics in the history and philosophy of science. Students may choose from a variety of regularly scheduled HPS lectures, including HPS seminars, Harris lectures, and Munroe seminars (history or philosophy of science only). Graded on attendance. *Not available for credit toward* *the humanities–social science requirement.* Graded pass/fail. Instructor: Visiting lecturers.

HPS 104. Forbidden Knowledge. *9 units (3-0-6).* When and how has the notion of freedom of knowledge and teaching in science emerged? What kinds of restrictions have been placed on scientists, their publications and institutions? Who restrained scientific knowledge of what sorts; for what reasons; and how successfully? These questions will be addressed by looking at some canonical cases in the history of science, such as Copernicus and Galileo. But we will also move into more recent history, discussing work on the atomic bomb, genetic engineering, and global warming. Not offered 2009–10.

HPS 105. Science and Literature. *9 units (3-0-6).* This course explores the relationships between the sciences and the humanities, from the point of view of literary-scientific interactions. Issues to be addressed include the "Two Cultures" debate over the years: Huxley vs. Arnold in the late 19th century; Snow vs. Leavis in the mid 20th century; the Science Wars of the late 20th century. Problems of representing scientific content in literary works and the consequences of examining scientific writing from a literary perspective will also be addressed. Readings will be drawn from a variety of genres, including novels, short stories, poetry, essays, and scientific texts. Not offered 2009–10.

HPS/Pl 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: Hitchcock. Given in alternate years; offered 2009–10.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6); first 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. Not offered 2009–10.

HPS/Pl 122. Confirmation and Induction. *9 units (3-0-6); offered by announcement.* Philosophical and conceptual issues arising from theories of confirmation and induction. Topics include Hume's "old" problem of induction; Goodman's "new" riddle of induction and various notions of "projectability"; inductive logic; Bayesian confirmation theory; and other theories of confirmation. Not offered 2009–10.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6); offered by announcement.* 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. Instructors: Hitchcock, Sauer.

HPS/Pl 125. Philosophical Issues in Quantum Physics. *9 units (3-0-6); second term.* This course will focus on conceptual issues that arise within quantum physics. Topics may include determinism and indeterminism; Einstein's critiques of quantum theory; the interpretation of quantum measurement; and quantum logic. Instructors: Hitchcock, Sauer.

HPS/Pl 128. Philosophy of Mathematics. *9 units (3-0-6).* An examination of conceptual issues that arise in mathematics. The sorts of issues addressed may include the following: Are mathematical objects such as numbers in some sense real? How do we obtain knowledge of the mathematical world? Are proofs the only legitimate source of mathematical knowledge? What is the relationship between mathematics and the world? How is it possible to apply abstract theory to the world? Views of major historical figures such as Plato, Hume, Kant, and Mill, as well as of contemporary writers are examined. The course will also examine philosophical issues that arise in particular areas of mathematics such as probability theory and geometry. Not offered 2009–10.

HPS/Pl 129. Introduction to Philosophy of Biology. *9 units (3-0-6).* Philosophical and conceptual issues relating to the biological sciences. Topics covered may include the logical structure of evolutionary theory, units of selection, optimization theory, the nature of species, reductionism, teleological and functional reasoning, and ethical issues arising from contemporary biological research. Not offered 2009–10.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6); first, second terms.* This course will examine the impact of recent advances in biological sciences for studies of the mind, behavior, and society. Topics may include evolutionary psychology, the relation between evolution and development, the impact of molecular genetics on the theory of evolution, mathematical modeling of evolution and artificial evolution, philosophical and social issues raised by modern molecular biology. Instructor: Cowie.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6); offered by announcement.* An introduction to the mind-body problem. The course attempts, from the time of Descartes to the present, to understand the nature of the mind and its relation to the body and brain. Topics to be addressed may include dualism, behaviorism, functionalism, computationalism, neurophilosophy, consciousness and qualia, scientific psychology vs. "folk" psychology, the nature of emotion, knowledge of other minds. Not offered 2009–10.

HPS/Pl 133. Philosophy and Neuroscience. *9 units (3-0-6); third term.* This course will examine the impact of recent advances in neuroscience on traditional philosophical problems. Topics may include the nature of free will in light of work on the neural basis of decision making; the nature of consciousness, knowledge, or learning; the mind/brain from the perspective of neural computation; and the neural foundations of cognitive science. Instructor: Quartz.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6); second, third terms.* An in-depth examination of one or more issues at the intersection of contemporary philosophy and the brain and behavioral sciences. Topics may include the development of a theory of mind and self-representation, theories of representation and neural coding, the nature of rationality, the nature and causes of psychopathology, learning and innateness, the modularity of mind. Instructors: Cowie, Machery.

HPS/Pl 136. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7); third term.* Course will address a number of ethical and philosophical issues arising in scientific research. Among the topics discussed will be the following: fraud and misconduct in science; various theories of the scientific method; the realities of science as practiced in laboratories and the pressures facing scientists in the real world; ethical issues raised by collaborative research; reward and credit in science; responsibilities of mentors, referees, and editors in the conduct of research; the role of government regulation and supervision in dealing with scientific misconduct; the role of the university; and changes in ethical standards due to advancing technology. Undergraduates wishing to take the course for advanced humanities credit should register for 9 units (a term paper will be required). Students who register for 4 units may do so on a pass/fail basis only. Instructors: Woodward, D. Goodstein. Not offered 2009–10.

HPS/Pl 137. Experimental Philosophy. *9 units (3-0-6); third term.* A survey of recent work in experimental philosophy: experimental studies aimed at advancing debates in a number of areas of philosophy including metaphysics, semantics, epistemology, philosophy of science, and ethics. Instructor: Machery.

HPS/Pl 138. Human Nature and Society. *9 units (3-0-6).* 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 156. The History of Modern Science. *9 units (3-0-6); third term.* Selected topics in the development of the physical and biological sciences since the 17th century. Not offered 2009–10.

Pl/HPS 157. Leibniz vs. Newton: Philosophers at War. *9 units (3-0-6).* For course description, see Philosophy.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6); second term.* The birth of modern Western science from 1400 to 1700. The course examines the intellectual revolution brought about by the contributions of Copernicus, Galileo, Descartes, Kepler, Newton, and Harvey, and their relation to major political, social, and economic developments.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6).* This course examines the growth of science in America after World War II, and its relation to Cold War geopolitics. Topics will include the growth of the American research university; the establishment and role of the national laboratory system; the role of federal funding agencies including ONR, NSF, NIH, and DARPA; and the impact of geopolitical considerations and priorities on scientific research and knowledge. Instructor: Oreskes.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6); first, third terms.* 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. Not offered 2009–10.

HPS/H 162. Social Studies of Science. *9 units (3-0-6), third term.* A comparative, multidisciplinary course that examines the practice of science in a variety of locales, using methods from the history, sociology, and anthropology of scientific knowledge. Topics covered include the high-energy particle laboratory as compared with a biological one; Western as compared to non-Western scientific reasoning; the use of visualization techniques in science from their inception to virtual reality; gender in science; and other topics. Instructor: Feingold.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6); third 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.* 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.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6); offered by announcement*. This course covers the development of electromagnetism and thermal science from its beginnings in the early 18th century through the early 20th century. Topics covered include electrostatics, magnetostatics, electrodynamics, Maxwell's field theory, the first and second laws of thermodynamics, and statistical mechanics as well as related experimental discoveries. Not offered 2009–10.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visiting lecturers.

HPS/Pl 169. Selected Topics in Philosophy of Science. *9 units (3-0-6); offered by announcement*. Instructors: Staff, visiting lecturers.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6); second term.* A study of the experimental, mathematical, and theoretical developments concerning light, from the time of Ptolemy in the 2nd century A.D. to the production of electromagnetic optics in the 20th century. Instructor: Buchwald.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6); second term. Prerequisite: basic Caltech physics course.* This course covers developments in mechanics, as well as related aspects of mathematics and models of nature, from just before the time of Galileo through the middle of the 18th century, which saw the creation of fluid and rotational dynamics in the hands of Euler and others. Not offered 2009–10.

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 2009–10.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6); first term.* This course examines developments in chemistry from medieval alchemy to the time of Lavoisier. It will examine the real content of alchemy and its contributions to modern science, as well as how to decode its bizarre language; chemistry's long quest for respect and academic status; the relations of chemistry with metallurgy, medicine, and other fields; and the content and development of the chemical theories and the chemical laboratory and its methods. Not offered 2009–10.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6); third term.* The course will highlight the background and some of the landmarks in the evolution of Greek astronomy from its tentative beginnings in the 5th century B.C., to its culmination in the work of Ptolemy in the 2nd century A.D. Instructor: Toomer.

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 2009–10.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6); second term*. Galileo's discoveries with the telescope and arguments for the heliocentric theory radically transformed the System of the World, as it was called, and resulted in his being brought before the Inquisition, the most famous single event in the history of science. The readings will be Galileo's *Sidereal Messenger*, *Letters on Sunspots*, *The Assayer*, *Dialogue on the Two Great Systems of the World*, and documents concerned with Galileo's conflicts with the Church in 1616 and 1633. Instructor: Swerdlow. Not offered 2009–10.

HPS/H 179. Cambridge Scientific Minds: How We See Them; How They See Themselves. *9 units (3-0-6).* Cambridge University has long been a world center for science. Using biography, autobiography, novel, and historical studies, this course will examine and analyze the thought of Newton, Darwin, Maxwell, Watson, Crick, and Hawking. Instructor: Wilson.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* This course will examine the interplay between the theoretical understanding of physical nature and the philosophical definition of reliable knowledge. It will investigate this intellectual interplay in the work of Galileo, Descartes, Newton, Hume, Maxwell, and Einstein. Instructor: Wilson.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* From treatises about geography and astronomy to the history of plants and animals, early modern Natural philosophy provided an astonishingly broad background of research agendas. The course will examine the manner in which observations were carried out and evidence weighed, both in university settings and in the field. Topics to be addressed include the changing perceptions regarding the reliability of the senses; the contribution of instruments to accumulation of reliable knowledge; the standardization of data and its presentation; and the emergence of new argumentative strategies. Instructor: Goeing.

HPS/H 182. Show and Tell: 3-D Models for the Visualization of Complex Concepts in the 16th and 17th Centuries. *9 units (3-0-6).* Early modern artists and scholars of all disciplines routinely built three-dimensional objects in order to represent complex concepts and appearances. Some rendered visible abstract formulas in geometrical forms like the movement of the stars; others schematized complex work-flows like drainage systems, or the geographical conditions on Earth; still others proposed costly projects, such as the cupola of St. Peter in Rome, on the basis of a model. These models—many of which still survive—were constructed according to precise rules and regulations, as well as personal taste. The course will offer an introduction to the significance of three-dimensional models in the early modern period, and the manner in which they were crafted and used by artists, physicians, and natural philosophers. Instructor: Goeing.

Pl/HPS 183. Bioethics. *9 units (3-0-6).* For course description, see Philosophy.

Pl/HPS 184. Science, Ethics, and Public Policy. *9 units (3-0-6).* For course description, see Philosophy.

HUMANITIES

Hum/H 1 ab. East Asian History. *9 units (3-0-6); offered by announcement.* Late imperial values, institutions, and behaviors and their evolution in the 19th and 20th centuries. Hum/H 1 a will deal largely with China, and Hum/H 1 b with Japan. The readings will consist of selected thematic texts as well as a chronological textbook. Each term is independent of the other, and students will normally take only one of the two terms. Not offered 2009–10.

Hum/H 2. American History. *9 units (3-0-6); offered by announcement.* Among the major events, trends, and problems of our country's history are the American Revolution, the framing and development of the Constitution, wars, slavery and emancipation, ethnic and gender relations, immigration, urbanization, westward conquest, economic fluctuations, changes in the sizes and functions of governments, foreign relations, class conflicts, domestic violence, and social and political movements. Although no one course can treat all of these themes, each freshman American history course will deal with two or more of them. How have American historians approached them? What arguments and evidence have scholars offered for their interpretations and how can we choose between them? In a word, what can we know about our heritage? Instructor: Kousser.

Hum/H 3 abc. European Civilization. *9 units (3-0-6); offered by announcement.* This course will be divided into three terms, each of which will focus on a coherent period in the history of European civilization. Each term is independent of the others, and students will normally take only one of the three terms.

a. The Classical and Medieval Worlds. 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. Instructors: Brown, Hoffman, Pigman.

b. Early Modern Europe. 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: Brown, Hoffman, Pigman, Crosignani, Dennison.

c. Modern Europe. 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, Rosenstone.

Hum/H 4 abc. Civilization, Science, and Archaeology. *9 units (3-0-6); offered by announcement.* This course will be divided into three terms, each of which will focus on a particular aspect of pre-classical antiquity or premodern science. Each term is independent of the others, and students will normally take only one of the three terms. Instructor: Buchwald.

a. Before Greece: The Origins of Civilization in Mesopotamia. 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.

b. The Development of Science from Babylon through the Renaissance. 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.

c. The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. 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.

Hum/En 5. Major British Authors. *9 units (3-0-6); offered by announcement.* This course will introduce students to some of the genres of English literature, including poetry, drama, and prose fiction, by studying major authors from different periods. Sometimes the course will cover a wide range of authors, while at others it will concentrate on a few. Authors might include Chaucer, Shakespeare, Milton, Austen, George Eliot, or Joyce. Instructors: Gilmartin, Haugen, La Belle, Mandel, Pigman.

Hum/En 6. American Literature and Culture. *9 units (3-0-6); offered by announcement.* Studies of American aesthetics, genres, and ideas from the birth of the nation to the present. Students will be introduced to the techniques of formal analysis. We will consider what constitutes evidence in relation to texts and how to develop a persuasive interpretation. Topics may include *Nature's Nation*, slavery and its aftermath, individualism and the marketplace, the "New Woman," and the relation between word and image. Instructors: Jurca, Weinstein.

Hum/En 7. Modern European Literature. *9 units (3-0-6); offered by announcement.* An introduction to literary analysis through a sustained exploration of the rise and aftermath of modernism. What was the modernist revolt of the early 20th century, how did it challenge literary tradition and existing social forms, and to what extent have we inherited a world remade by modernism? While the course will focus on British and Continental literature, writers from other parts of the world whose work closely engages the European tradition may also be considered. Authors may include Flaubert, James, Conrad, Joyce, Woolf, Kafka, Borges, Yeats, and Eliot. Instructors: Baskin, Gilmartin, Haugen, Pigman.

Hum/Pl 8. Right and Wrong. *9 units (3-0-6); offered by announcement.* This course addresses the question "Where do moral ideas come from and how should they guide our conduct?" by exploring selections from the great works of moral and political philosophy—Aristotle's *Nichomachean Ethics*, Plato's *Republic*, Hobbes's *Leviathan*, Locke's *Second Treatise on Government*, Mill's *Utilitarianism*, Rousseau's *The Social Contract*, Kant's *Groundings for a Metaphysics of Morals*, Rawls's *A Theory of Justice*—as well as a variety of more modern texts and commentaries. Throughout, an attempt will be made to acquaint students with the basic elements of Western moral and political tradition: notions about human rights, democracy, and the fundamental moral equality of all human beings. This historical approach will then provide a background for the issues that frame contemporary discussions of moral and political ideas. Instructor: Philosophy staff.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6); offered by announcement.* The theme of this course is the scope and limitations of rational belief and knowledge. Students will examine the nature of reality, the nature of the self, the nature of knowledge, and how we learn about the natural world. Students will be introduced to these issues through selections from some of the world's greatest philosophical works, including Descartes's *Meditations*, Pascal's *Pensées*, Hume's *Enquiry Concerning Human Understanding*, Berkeley's *Principles of Human Knowledge*, and Kant's *Prolegomena to any Future Metaphysics.* A variety of more contemporary readings will also be assigned. Instructor: Philosophy staff.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6); offered by announcement.* Major topics include the following: What are the origins of modern Western science, when did it emerge as distinct from philosophy and other cultural and intellectual productions, and what are its distinguishing features? When and how did observation, experiment, quantification, and precision enter the practice of science? What were some of the major turning points in the history of science? What is the changing role of science and technology? Using primary and secondary sources, students will take up significant topics in the history of science, from ancient Greek science to the 20th-century revolution in physics, biology, and technology. Hum/H/HPS 10 may be taken for credit toward the additional 36-unit HSS requirement by HPS majors and minors who have already fulfilled their freshman humanities requirement and counts as a history course in satisfying the freshman humanities breadth requirement. Instructor: History staff.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6); offered by announcement.* A consideration of the entire history of astronomy and cosmology, the oldest of all the sciences, from antiquity to the late 20th century, from the Babylonians to the Big Bang. The course will be devoted to repeating the procedures used in earlier astronomy and working directly with the primary sources. Instructor: Swerdlow.

F/Hum 32. Humanities on Film. *3 units (1-1-1).* For course description, see Film.

Hum 119. Selected Topics in Humanities. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visitors.

INDEPENDENT STUDIES PROGRAM

Students who have chosen to enter the Independent 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 page 223 for complete details.

INFORMATION SCIENCE AND TECHNOLOGY

IST 1. Introduction to Information. *9 units (3-0-6); third term.* This course offers an introduction to the modern study of information, addressing fundamental questions about information representation, transmission, and learning. Questions considered include: What is information, and how should we represent it for storage and transmission? What does it mean to represent information efficiently? Is there a "shortest possible" description? Can we hope to communicate reliably in a noisy world? How much information can be transmitted, and what are the strategies by which we can improve reliability? What does it mean for a machine to learn? How much data must be observed to achieve reliable learning? Not offered on a pass/ fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Instructor: Effros.

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.* Instructor: Bruck.

LANGUAGES

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L 1. Selected Topics in Language. *Units to be determined by arrangement with the instructor.* Graded pass/fail. Instructors: Staff, visiting lecturers.

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 2009–10.

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. Instructors: Orcel, de Bedts.

L 103 abc. Intermediate French. *9 units (3-0-6); first, second, third terms. Prerequisite: L 102 abc or equivalent.* The first two terms feature an extensive grammar review and group activities that promote self-expression. Op-Ed articles and a series of literary texts provide a basis for classroom discussion and vocabulary expansion. Several short written compositions are required. The third term is designed to further develop an active command of the language. A variety of 19th- and 20th-century short stories are discussed in class to improve comprehension and oral proficiency. Students are expected to do an oral presentation, to write four short compositions, and a final paper. Second and third terms are offered for advanced humanities credit. Instructors: de Bedts, Orcel.

L/F 104. French Cinema. *9 units (3-0-6); first term. Prerequisite: 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, Carné, 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. Instructor: Orcel.

L 105 ab. Topics in French Culture and Literature. *9 units (3-0-6); second term. L 105 a and L 105 b taught in alternate years. Prerequisite: L 103 abc or equivalent.* Part a: 20th-century French literature. Part b: Contemporary France. Conducted in French. Offered for advanced humanities credit. Instructor: Orcel.

L 106 abc. Elementary Japanese. *9 units (5-0-4); first, second, third terms.* 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. Not offered on a pass/fail basis. Instructor: Hirai.

L 107 abc. Intermediate Japanese. *10 units (5-1-4); first, second, third terms. Prerequisite: L 106 abc or equivalent.* Continued instruction and practice in conversation, building up vocabulary, and understanding complex sentence patterns. The emphasis, however, will be on developing reading skills. Recognition of approximately 1,000 characters. Not offered on a pass/fail basis. Instructor: Hirata.

L 108 abc. Advanced Japanese. *10 units (3-1-6); first, second, third terms. Prerequisite: L 107 abc or equivalent.* Developing overall language skills. Literary and newspaper readings. Technical and scientific translation. Improvement of listening and speaking ability so as to communicate with Japanese people in real situations. Recognition of the 1,850 "general-use characters." Not offered on a pass/fail basis. Instructor: Hirata.

L 110 abc. Elementary Spanish. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in understanding, speaking, reading, and writing Spanish. Exclusively for students with no previous knowledge of Spanish. Instructors: Garcia, Arjona.

L 112 abc. Intermediate Spanish. *9 units (3-0-6); first, second, third terms. Prerequisite: L 110 abc or equivalent.* Grammar review, vocabulary building, practice in conversation, and introduction to relevant history, literature, and culture. Literary reading and writing are emphasized in the second and third terms. Students who have studied Spanish elsewhere must consult with the instructor before registering. Instructors: Garcia, Arjona.

L 114 abc. Spanish and Latin American Literature. *9 units (3-0-6); offered by announcement. Prerequisite: 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. Instructors: Garcia, Arjona.

L 130 abc. Elementary German. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in aural comprehension, speaking, reading, and writing. Students who have had German in secondary school or college must consult with the instructor before registering. Instructor: Aebi.

L 132 abc. Intermediate German. *9 units (3-0-6); first, second, third terms. Prerequisite: L 130 abc or equivalent.* Reading of short stories and plays, grammar review, aural and oral drills and exercises, expansion of vocabulary, and practice in reading, writing, and conversational skills. Second and third terms will emphasize written expression, technical/scientific translation, and literary readings. Students who have studied German elsewhere must consult with the instructor before registering. Instructor: Aebi.

L 140 abc. German Literature. *9 units (3-0-6). Prerequisite: L 132 c or equivalent (two years of college German), or instructor's permission.* Reading and discussion of works by selected 12th–21st-century authors, current events on Internet/TV, exposure to scientific and technical writing, business communication. Viewing and discussion of German-language films. Conducted in German. Not offered 2009–10.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6).* For course description, see History.

L 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); first, third terms.* First term: French classical literature of the 17th and 18th centuries; third term: reading and discussion of works by selected 19th- and 20th-century authors. The approach is both historical and critical. Conducted in English, but students may read the French originals. Film versions of the texts studied may be included. Instructors: de Bedts, Orcel.

L 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. Instructor: Staff.

L 167 abc. Latin Literature. *9 units (3-0-6); first, second, third terms. Prerequisite: three years of high-school Latin.* Major works of Latin literature, usually one per term. No work will be studied more than once in four years, and students may repeat the course for credit. Instructor: Staff.

L 170 abc. Introduction to Chinese. *10 units (4-1-5); first, second, third terms.* An introductory course in standard Chinese (Mandarin) designed for students with no previous knowledge of the language. The course introduces the fundamentals of Chinese, including pronunciation, grammar, and Chinese characters, emphasizing the four basic language skills: listening, speaking, reading, and writing. By the end of the three-term sequence, students will have acquired knowledge of basic rules of grammar and the ability to converse, read, and write on simple topics of daily life, and will have command of more than 800 Chinese compounds and 700 characters. Instructor: Wang.

L 171 abc. Elementary Chinese. *9 units (5-0-4); first, second, third terms. Prerequisite: placement exam results or instructor's permission.* A fast-paced course for students who have had prior exposure to the language. Students are introduced to the basic principles of written and oral communication. Emphasis will be placed on consolidating basic grammar, and developing the ability to use the language creatively in talking about oneself and in dealing with daily situations within a Chinese cultural context. Instructor: Wang.

L 172 abc. Intermediate Chinese. *10 units (4-1-5); first, second, third terms. Prerequisite: L 170 abc or L 171 abc or equivalent.* A course designed to meet the personal interests and future professional goals of students who have had one year of elementary modern Chinese. Students will learn new vocabulary, sentence patterns, idiomatic expressions, and proverbs, as well as insights into Chinese society, culture, and customs. Instructor: Ming.

L 173 ab. Advanced Chinese. *10 units (3-1-6); first, second terms. Prerequisite: L 172 abc or equivalent.* A course designed to further develop overall language proficiency through extensive reading of selected texts representing a wide variety of styles and genres, including newspapers and magazines, visual materials, and a selection of works of major modern writers. Classes are conducted primarily in Chinese. Instructor: Ming.

L 174. Topics in Chinese Literature. *9 units (3-0-6); third term. Prerequisite: 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. Instructor: Ming.

LAW

Law 33. Introduction to the Law. *9 units (3-0-6); first term.* An introduction to Anglo-American law from both the legal and the social-scientific points of view. Subject can vary from year to year. Available for introductory social science credit. Instructor: Spitzer.

Law 134. Law and Technology. *9 units (3-0-6); second term.* A sophisticated introduction to and exploration of the intersection of science and the law, focusing on the intellectual property system and the various means by which the conduct and products of scientific research are regulated. The course will analyze and compare American, international, and theoretical alternative systems, in part by means of economics modeling. The latter portion of the course will explore a particular scientific area in depth, typically using guest lecturers or coteachers to convey the science element (examples include the human genome project; the Internet and cyberspace; the law of the sea; and outer-space exploration). Some background in law and economics would be helpful. Not offered 2009–10.

Law 135. History of Anglo-American Law. *9 units (3-0-6); second term.* An introductory survey of English law from medieval to modern times, with discussion of parallel and divergent developments in the United States. Topics include the constitution: constraints on the king, Magna Carta, the rise of parliamentary democracy, the role of courts, written versus unwritten constitutions, the U.S. Constitution; law making: statutes and the doctrine of precedent; fact finding: trial by battle and by ordeal, the development of the jury trial; civil justice: common law, equity, contract, and property law; criminal justice: private and public prosecution, star chamber, defendants' rights, criminal sanctions; family law and the changing legal status of women. Instructor: Klerman.

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-class materials-science majors. Starting with an open-ended topic, students will plan and execute a project in materials science and engineering that includes written and oral reports based upon actual results, synthesizing topics from their coursework. 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. Not offered 2009–10.

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.

MS 105. Phase Transformations. *9 units (3-0-6); third term. Prerequisite: APh 105 b or ChE/Ch 164, or instructor's permission.* Thermodynamics and kinetics of phase transformations. Phase diagrams for decomposition and ordering. Nucleation, spinodal decomposition, microstructural morphologies. Role of strain energy in solid-solid phase transformations. Thermomechanical processing of selected materials. Taught concurrently with APh 105 c. Instructors: Johnson, Fultz.

MS 110 abc. Materials Research Lectures. *1 unit; first, second, third terms.* A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructor: Snyder.

MS 115 ab. Fundamentals of Materials Science. *9 units (3-0-6); first, second terms. Prerequisite: 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. In the first term, emphasis is on the relationships between chemical bonding, crystal structure, thermodynamics, phase equilibria, microstructure, and properties. In the second term, generic processing and manufacturing methods are presented for each class of materials with particular focus on the influence of these processes on mechanical properties. Emphasis is placed on the basic materials science behind each processing method, covering such topics as thermodynamics, diffusion, kinetics of phase transformations, and microstructure development. Instructors: Haile, van de Walle.

MS 125. Advanced Transmission Electron Microscopy. *9 units (1-6-2); third term. Prerequisite: MS 132.* Diffraction contrast analysis of crystalline defects. Phase contrast imaging. Physical optics approach to dynamical electron diffraction and imaging. Microbeam methods for diffraction and imaging. Chemical analysis by energy dispersive X-ray spectrometry and electron energy loss spectrometry. Instructor: Ahn.

MS 130. Diffraction and Structure. *9 units (3-0-6); first term. Prerequisite: graduate standing or instructor's permission.* Content is identical to MS 132 but without the laboratory exercises. Instructor: Fultz.

MS 131. Structure and Bonding in Materials. *9 units (3-0-6); second term. Prerequisite: graduate standing or introductory quantum mechanics.* Atomic structure, hybridization, molecular orbital theory, dependence of chemical bonding on atom configurations. Covalency, ionicity, electronegativity. Madelung energy. Effects of translational periodicity on electron states in solids. Band structures of group IV semiconductors; transition metals and ferromagnetism. Structural features of materials such as point defects, dislocations, disclinations, and surfaces. Structures of defects calculated with the embedded atom method. Instructor: van de Walle.

MS 132. Diffraction and Structure of Materials. *12 units (3-3-6); first term.* Principles of electron and X-ray diffraction, with applications for characterizing materials. Topics include scattering and absorption of electrons and X rays by atoms. The transmission electron microscope (TEM) and the X-ray diffractometer. Kinematical theory of diffraction: effects of strain, size, disorder, and temperature. Crystal defects and their characterization. A weekly laboratory will complement the lectures. Instructors: Fultz, Ahn.

MS 133. Kinetic Processes in Materials. *9 units (3-0-6); third term. Prerequisites: 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: Fultz and Kornfield.

MS 142. Application of Diffraction Techniques in Materials Science. *9 units (2-3-4); third term. Prerequisites: MS 132 or instructor's permission.* Applications of X-ray and neutron diffraction methods to the structural characterization of materials. Emphasis is on the analysis of polycrystalline materials but some discussion of single crystal methods is also presented. Techniques include quantitative phase analysis, crystalline size measurement, lattice parameter refinement, internal stress measurement, quantification of preferred orientation (texture) in materials, Rietveld refinement, and determination of structural features from small angle scattering. Homework assignments will focus on analysis of diffraction data. Samples of interest to students for their thesis research may be examined where appropriate. Instructor: Haile.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6); third term.* Thermodynamics and kinetics of ion and electron transport in solids, with emphasis on processes in electrolyte and electrode materials used in energy storage and conversion. Treatment of electroanalytical characterization techniques including a.c. impedance spectroscopy, voltammetry, and d.c. polarization methods. Application areas include fuel cells, electrochemical gas separation membranes, batteries, supercapacitors, and hydrogen storage materials. Not offered 2009–10.

MS/ME 161. Imperfections in Crystals. *9 units (3-0-6); third term. Prerequisites: Graduate standing or MS 115 a.* 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. Instructor: Greer.

MS/ME 162. Mechanical Behavior of Materials. *9 units (3-0-6); first term. Prerequisites: MS/ME 161 or equivalent*. Introduction to the mechanical behavior of solids, emphasizing the relationships between microstructure, defects, and mechanical properties. Elastic, anelastic, and plastic properties of crystalline and amorphous materials. Polymer and glass properties: viscoelasticity, flow, and strain-rate dependence. The relationships between stress, strain, strain rate, and temperature for deformable solids. Application of dislocation theory to strengthening mechanisms in crystalline solids. The phenomena of creep, fracture, and fatigue, and their controlling mechanisms. Instructor: Greer.

ME/EST 199. Special Topics in Energy Science and Technology. Units to be arranged. Subject matter will change from term to term depending upon staff and student interest, but will generally center on modes of energy storage and conversion. Instructor: Staff.

MS 200. Advanced Work in Materials Science. The staff in materials science will arrange special courses or problems to meet the needs of advanced graduate students.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

ME/MS 260 abc. Micromechanics. *12 units (3-0-9).* For course description, see Mechanical Engineering.

MS 300. Thesis Research.

MATHEMATICS

Ma 1 abc. Calculus of One and Several Variables and Linear Algebra. *9 units (4-0-5); first, second, third terms. Prerequisites: high-school algebra, trigonometry, and calculus. Special section of Ma 1 a, 12 units (5-0-7).* Review of calculus. Complex numbers, Taylor polynomials, infinite series. Comprehensive presentation of linear algebra. Derivatives of vector functions, multiple integrals, line and path integrals, theorems of Green and Stokes. Ma 1 b, c is divided into two tracks: analytic and practical. Students will be given information helping them to choose a track at the end of the fall term. There will be a special section or sections of Ma 1 a for those students who, because of their background, require more calculus than is provided in the regular Ma 1 a sequence. These students will not learn series in Ma 1 a and will be required to take Ma 1 d. Instructors: Ryckman, Graber, Wilson, Aschbacher, Rains, Ramakrishnan.

Ma 1 d. Series. *5 units (2-0-3); second term only. Prerequisite: special section of Ma 1 a.* This is a course intended for those students in the special calculus-intensive sections of Ma 1 a who did not have complex numbers, Taylor polynomials, and infinite series during Ma 1 a. It may not be taken by students who have passed the regular Ma 1 a. Instructor: Staff.

Ma 2 ab. Differential Equations, Probability and Statistics. *9 units (4-0-5); first, second terms. Prerequisite: Ma 1 abc.* Ordinary differential equations, probability, statistics. Instructors: Flach, Makarov, Borodin.

Ma 3. 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 $a^n + b^n = c^n$ and $a^2 - db^2 = \pm 1$, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Balasubramanyam.

Ma 4. Introduction to Mathematical Chaos. *9 units (3-0-6); third term.* An introduction to the mathematics of "chaos." Period doubling universality, and related topics; interval maps, symbolic itineraries, stable/unstable manifold theorem, strange attractors, iteration of complex analytic maps, applications to multidimensional dynamics systems and real-world problems. Possibly some additional topics, such as Sarkovski's theorem, absolutely continuous invariant measures, sensitivity to initial conditions, and the horseshoe map. Instructor: Ryckman.

Ma 5 abc. Introduction to Abstract Algebra. *9 units (3-0-6); first, second, third terms. Freshmen must have instructor's permission to register.* 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: Ramakrishnan, Agarwala.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisite: for Ma/CS 6 c, Ma/CS 6 a or Ma 5 a or instructor's permission.* First term: a survey emphasizing graph theory, algorithms, and applications of algebraic structures. Graphs: paths, trees, circuits, breadth-first and depth-first searches, colorings, matchings. Enumeration techniques; formal power series; combinatorial interpretations. Topics from coding and cryptography, including Hamming codes and RSA. Second term: directed graphs; networks; combinatorial optimization; linear programming. Permutation groups; counting nonisomorphic structures. Topics from extremal graph and set theory, and partially ordered sets. Third term: elements of computability theory and computational complexity. Discussion of the P=NP problem, syntax and semantics of propositional and first-order logic.

Introduction to the Gödel completeness and incompleteness theorems. Instructors: Wilson, Balachandran, Epstein.

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: Lyons.

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: Borodin.

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: Wilson.

Ma 12. Chance. *9 units (4-0-5); second term. Prerequisite: Ma 2 b (probability and statistics).* This course will explore examples of the use and misuse of notions of probability and statistics in popular culture and in scientific research. Basic ideas about random fluctuations will be introduced, along with simple techniques like nonparametric statistics and the bootstrap. Not offered 2009–10.

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: Nelson.

Ma 91 a. Homological Algebra. *9 units (3-0-6); first term. Prerequisite: Ma 5 or instructor's permission.* This course will be a first introduction to homological algebra, covering generalities on additive and abelian categories; the category of complexes, and the long exact sequence of cohomology; cones and homotopies; the homotopic category of complexes; projective and injective resolutions, and the derived category;

derived functors; double complexes; spectral sequences; and further topics as time permits. Not offered 2009–10.

Ma 92 abc. Senior Thesis. *9 units (0-0-9); first, second, third terms. Prerequisite: To register, the student must obtain permission of the mathematics undergraduate representative, Richard Wilson.* Open only to senior mathematics majors who are qualified to pursue independent reading and research. This research must be supervised by a faculty member. The research must begin in the first term of the senior year and will normally follow up on an earlier SURF or independent reading project. Two short presentations to a thesis committee are required: the first at the end of the first term and the second at the midterm week of the third term. A draft of the written thesis must be completed and distributed to the committee one week before the second presentation. Graded pass/fail in the first and second terms; a letter grade will be given in the third term.

Ma 98. Independent Reading. *3–6 units by arrangement.* Occasionally a reading course will be offered after student consultation with a potential supervisor. Topics, hours, and units by arrangement. Graded pass/fail.

Ma 105. Elliptic Curves. *9 units (3-0-6); first term. Prerequisite: Ma 5, Ma 3, or equivalents.* 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. Instructor: Balasubramanyam.

Ma 108 abc. Classical Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 2 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: Van de Bult, Lee, Ryckman.

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: Wilton, Gholampour.

Ma 110 abc. Analysis, I. *9 units (3-0-6); first, second, third terms.Prerequisite: Ma 108 or previous exposure to metric space topology, Lebesgue measure.* First term: integration theory and basic real analysis: topological spaces, Hilbert space basics, Fejer's theorem, measure theory, measures as functionals, product measures, L^p-spaces, Baire category, Hahn-Banach theorem, Alaoglu's theorem, Krein-Millman theorem, countably normed spaces, tempered distributions and the Fourier transform. Second term: basic complex analysis: analytic functions, conformal maps and fractional linear transformations, idea of Riemann surfaces, elementary and some special functions, infinite sums and products, entire and meromorphic functions, elliptic functions. Third term: harmonic analysis; operator theory. Harmonic analysis: maximal functions and the Hardy-Littlewood maximal theorem, the maximal and Birkoff ergodic theorems, harmonic and subharmonic functions, theory of H^p-spaces and boundary values of analytic functions. Operator theory: compact operators, trace and determinant on a Hilbert space, orthogonal polynomials, the spectral theorem for bounded operators. If time allows, the theory of commutative Banach algebras. Instructors: Simon, Duits.

Ma 111 ab. Analysis, II. *9 units (3-0-6); first, second terms. Prerequisite: 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. First term: Reproducing Hilbert spaces. Second term: Quasiconformal maps and their applications. Instructors: Duits, Makarov.

Ma 112 ab. Statistics. *9 units (3-0-6); first, second terms. 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 2009–10.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or instructor's permission.* Propositional logic, predicate logic, formal proofs, Gödel completeness theorem, the method of resolution, elements of model theory. Computability, undecidability, Gödel incompleteness theorems. Axiomatic set theory, ordinals, transfinite induction and recursion, iterations and fixed points, cardinals, axiom of choice. Instructors: Epstein, Kechris.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or instructor's permission.* Various approaches to computability theory, e.g., Turing machines, recursive functions, Markov algorithms; proof of their equivalence. Church's thesis. Theory of computable functions and effectively enumerable sets.

Decision problems. Undecidable problems: word problems for groups, solvability of Diophantine equations (Hilbert's 10th problem). Relations with mathematical logic and the Gödel incompleteness theorems. Decidable problems, from number theory, algebra, combinatorics, and logic. Complexity of decision procedures. Inherently complex problems of exponential and superexponential difficulty. Feasible (polynomial time) computations. Polynomial deterministic vs. nondeterministic algorithms, NP-complete problems and the P = NP question. Not offered 2009–10.

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 2009–10.

Ma 120 abc. Abstract Algebra. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent. Undergraduates who have not taken Ma 5 must have instructor's permission.* Basic theory of groups, rings, modules, and fields, including free groups; Sylow's theorem; solvable and nilpotent groups; factorization in commutative rings; integral extensions; Wedderburn theorems; Jacobson radical; semisimple, projective, and injective modules; tensor products; chain conditions; Galois theory; cyclotomic extensions; separability; transcendental extensions. Instructors: Aschbacher, Mantovan.

Ma 121 abc. Combinatorial Analysis. *9 units (3-0-6); first, 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: Balachandran, van de Bult.

Ma 122 ab. Topics in Group Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ma 5 abc or instructor's permission.* Groups of Lie type: classical groups, Coxeter groups, root systems, Chevalley groups, weight theory, linear algebraic groups, buildings. Not offered 2009–10.

Ma 123. Classification of Simple Lie Algebras. *9 units (3-0-6); third term. Prerequisite: Ma 5 or equivalent.* This course is an introduction to Lie algebras and the classification of the simple Lie algebras over the complex numbers. This will include Lie's theorem, Engel's theorem, the solvable radical, and the Cartan Killing trace form. The classification of simple Lie algebras proceeds in terms of the associated reflection groups and a classification of them in terms of their Dynkin diagrams. Not offered 2009–10.

EE/Ma 126 ab. Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

Ma 130 abc. Algebraic Geometry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 120 (or Ma 5 plus additional reading).* Plane curves, rational functions, affine and projective varieties, products, local properties, birational maps, divisors, differentials, intersection numbers, schemes, sheaves, general varieties, vector bundles, coherent sheaves, curves and surfaces. Instructors: Graber, Morin, Gholampour.

Ma 131. Algebraic Geometry of Curves. *9 units (3-0-6); second term. Prerequisites: Ma 5, Ma 108, and Ma 109, or equivalent.* The theory of algebraic curves is a central branch of mathematics, having relations to fields as diverse as complex analysis, number theory, combinatorics, codes, topology, representation theory, and physics. The aim of the course is to give a substantial introduction to this subject. The topics will include affine and projective plane curves, mappings, differentials, divisors and line bundles, Jacobians, sheaves, cohomology, and moduli. Important results such as Riemann-Roch theorem, Hurwitz's theorem, and Abel's theorem will be discussed. Instructor: Graber.

Ma 135 ab. Arithmetic Geometry. *9 units (3-0-6); first, second terms. Prerequisite: Ma 130.* The course deals with aspects of algebraic geometry that have been found useful for number theoretic applications. Topics will be chosen from the following: general cohomology theories (étale cohomology, flat cohomology, motivic cohomology, or p-adic Hodge theory), curves and Abelian varieties over arithmetic schemes, moduli spaces, Diophantine geometry, algebraic cycles. Instructor: Morin.

Ma 140 abc. Functional Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 110.* First term: Basic spectral theory. Second term: C*-algebras. Third term: Advanced spectral theory. Instructors: Agarwala, Marcolli, Duits.

Ma/ACM 142 abc. Ordinary and Partial Differential Equations. *9 units (3-0-6); first, second, third terms. 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. Instructors: Zinchenko, Kang. Not offered 2009–10.

Ma/ACM 144 ab. Probability. *9 units (3-0-6); first, second terms.* 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. Instructors: Kang, Lee.

Ma 145 abc. Introduction to Unitary Group Representations. *9 units (3-0-6); first, second, third terms.* The study of representations of a group by unitary operators on a Hilbert space, including finite and compact groups, and, to the extent that time allows, other groups. First term: general representation theory of finite groups. Frobenius's theory of representations of semidirect products. The Young tableaux and the representations of symmetric groups. Second term: the Peter-Weyl theorem. The classical compact groups and their representation theory. Weyl character formula. Third term: Quantum Groups. Instructors: Borodin, Rains, van de Bult.

Ma 147 abc. Dynamical Systems. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 108, Ma 109, or equivalent.* First term: real dynamics and ergodic theory. Second term: Hamiltonian dynamics. Third term: complex dynamics. Instructor: Makarov. Not offered 2009–10.

Ma 148. Topics in Mathematical Physics: Hamiltonian Dynamics. *9 units (3-0-6); first term.* This course will study the Hamiltonian formalism of classical mechanics. Topics will include symplectic structures on finite-dimensional vector spaces, Hamiltonian vector fields, Poisson brackets, symplectic manifolds, Darboux's theorem, canonical transformations, normal forms near a critical point of the Hamiltonian, completely integrable systems, and some elements of KAM theory. Not offered 2009–10.

Ma 151 abc. Algebraic and Differential Topology. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 108 ab 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: Calegari, Wang.

Ma 157 ab. Riemannian Geometry. *9 units (3-0-6); second, third terms. Prerequisite: Ma 151 or equivalent, or instructor's permission.* Part a: basic Riemannian geometry: geometry of Riemannian manifolds, connections, curvature, Bianchi identities, completeness, geodesics, exponential map, Gauss's lemma, Jacobi fields, Lie groups, principal bundles, and characteristic classes. Part b: basic topics may vary from year to year and may include elements of Morse theory and the calculus of variations, locally symmetric spaces, special geometry, comparison theorems, relation between curvature and topology, metric functionals and flows, geometry in low dimensions. Instructors: Wang, Calegari. Part a not offered 2009–10.

Ma 160 abc. Number Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5.* In this course, the basic structures and results of algebraic number theory will be systematically introduced. Topics covered will include the theory of ideals/divisors in Dedekind domains, Dirichlet unit theorem and the class group, p-adic fields, ramification, Abelian extensions of local and global fields. Instructors: Balasubramanyam, Mantovan.

Ma 162 abc. Topics in Number Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 160.* The course will discuss in detail some advanced topics in number theory, selected from the following: Galois representations, elliptic curves, modular forms, L-functions, special values, automorphic representations, p-adic theories, theta functions, regulators. Instructor: Ramakrishnan. Only part c offered 2009–10.

Note: The courses labeled Ma 191, Ma 192, etc., are topics courses. Different courses are offered each year, reflecting the interests of faculty, visiting faculty, and students. Those offered in the fall term have an "a" designation, and "b" and "c" denote winter and spring. None of these courses is a prerequisite for any other.

Ma 191 a. Geometric Invariant Theory and Moduli Spaces. *9 units (3-0-6); first term.* The course will discuss geometric invariant theory (GIT) and its application to the construction of Moduli spaces. GIT has been successfully applied to the construction of moduli spaces of curves, vector bundles, abelian varieties and many other objects in algebraic geometry. We will start with some examples to illustrate the main ideas and continue with the notion of stability. We will then apply GIT to the construction of moduli spaces of curves and vector bundles over curves, and shall discuss other applications if time allows. Instructor: Gholampour.

Ma 191 b. Topics in Special Functions. *9 units (3-0-6); second term.* The course will cover various generalizations of Gauss' hypergeometric function, focusing especially on q- and elliptic analogues, as well as extensions to multiple variables. Topics include the Selberg integral (and generalizations), the associated orthogonal polynomials (Heckman-Odpam, Macdonald, Koornwinder), and generalizations of the Painlevé equations. Instructor: Rains.

Ma 191 c. Noncommutative Geometry, Part II. *9 units (3-0-6); third term.* This course will focus on the interplay between noncommutative geometry and arithmetic geometry, with special emphasis on the use of tools from quantum statistical mechanics and quantum field theory in number theoretic settings. Instructor: Marcolli.

Ma 192 a. Topics in Conformal Field Theory. *9 units (3-0-6); first term. Prerequisite: Ma 108 or instructor's permission.* The course will discuss a mathematical introduction to conformal field theory. Topics will cover Fock space, Feynman calculus, Gaussian free field, Feigin-Fuchs-Miura transform, stress-energy tensor, Ward identities, chiral vertex fields, and applications in representation theory. The course will present relations between conformal field theory and Schramm-Loewner evolutions in the chordal, radial, and dipolar case, respectively. Instructor: Kang.

Ma 192 b. Introduction to Heegaard Floer Homology. *9 units (3-0-6); second term.* This course will discuss the definition and basic properties of Heegaard Floer homology. Topics include J-holomorphic curves, Morse homology (infinite-dimensional), knot Floer homology, contact structures, combinatorial descriptions, and application to classical three- and four-dimensional topology. Instructor: Wang.

Ma 192 c. Introduction to Four-dimensional Topology. *9 units (3-0-6); third term.* This course will discuss the definition and basic properties of Heegaard Floer homology. Topics include J-holomorphic curves, Morse homology (infinite-dimensional), knot Floer homology, contact structures, combinatorial descriptions, and application to classical three- and four-dimensional topology. Instructor: Ni.

Ma 193 a. Krein-de Branges Spaces and Classical Problems of Linear Complex Analysis. *9 units (3-0-6); first term.* Krein-De Branges spaces of entire functions, canonical systems and Krein-De Branges solution of the inverse spectral problem, related questions of linear complex analysis (polynomial and exponential density and moment problems, completeness and minimality, gap theorems). Instructor: Makarov.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6).* For course description, see Social Science.

Ma 290. Reading. *Hours and units by arrangement.* Occasionally, advanced work is given through a reading course under the direction of an instructor.

Note: The following research courses and seminars, intended for advanced graduate students, are offered according to demand. They cover selected topics of current interest. The courses offered, and the topics covered, will be announced at the beginning of each term.

Ma 316 abc. Seminar in Mathematical Logic. Instructor: Kechris.

Ma 324 abc. Seminar in Combinatorics. Instructor: Wilson.

Ma 325 abc. Seminar in Algebra. Instructor: Aschbacher.

Ma 345 abc. Seminar in Analysis and Dynamics. Instructors: Borodin, Makarov.

Ma 348 abc. Seminar in Mathematical Physics. Instructor: Simon.

Ma 351 abc. Seminar in Geometry and Topology. Instructor: Calegari.

Ma 352 abc. Seminar in Algebraic Geometry. Instructor: Graber.

Ma 360 abc. Seminar in Number Theory. Instructors: Flach, Mantovan, Ramakrishnan.

Ma 390. Research. *Units by arrangement.*

Ma 392. Research Conference. *Three terms.*

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.

ME 18 ab. Thermodynamics. *9 units (3-0-6); second, third terms. Prerequisites: Ph 1 and Ph 2 (may be taken concurrently).* An introduction to classical thermodynamics with engineering applications. First term includes the first and second laws; closed and open systems; properties of a pure substance; availability and irreversibility; generalized thermodynamic relations. Second term emphasizes applications: gas and vapor power cycles; propulsion; mixtures; combustion and thermochemistry; chemical equilibrium. Instructors: Hunt, staff.

ME 19 ab. Fluid Mechanics. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2, Ph 1 abc.* Properties of fluids, basic equations of fluid mechanics, theorems of energy, linear and angular momentum. Euler's equations, inviscid potential flow, surface waves, airfoil theory. Navier-Stokes equations, vorticity and vorticity transport. Flow of real fluids, similarity parameters, flow in ducts. Boundary layer theory for laminar and turbulent flow, transition to turbulence. Drag, lift, and propulsion. Instructor: Brennen.

ME 20. Heat Transfer. *9 units (3-0-6); third term. Prerequisites: ME 18 ab, ME 19 ab.* An introduction to heat transfer. Steady-state and transient conduction, including numerical solutions. Forced and natural convective-heat transfer. Heat exchangers. Radiative heat transfer and solar energy. Taught concurrently with ME 119 a. Instructor: Staff.

ME 35 abc. Statics and Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Introduction to statics and dynamics of rigid and deformable bodies. Equilibrium of force systems, principle of virtual work, distributed force systems, friction, static analysis of rigid and deformable structures, kinematics, particle dynamics, rigid-body dynamics, dynamics of deformable systems, and vibrating systems. Instructors: Bhattacharya, Hall.

ME 65. Mechanics of Materials. *9 units (3-0-6); first term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to continuum mechanics, principles of elasticity, plane stress, plane strain, axisymmetric problems, stress concentrations, thin films, fracture mechanics, variational principles, frame structures, finite element methods, composites, and plasticity. Taught concurrently with Ae/AM/CE/ME 102. Instructor: Daraio.

ME 66. Vibration. *9 units (3-0-6); third term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to vibration and wave propagation in continuous and discrete multi-degree-of-freedom systems. Strings, mass-spring systems, mechanical devices, elastic continua. Equations of motion, Lagrange's equations, Hamilton's principle, and time-integration schemes. Instructor: Heaton.

ME 71. Introduction to Engineering Design. *9 units (3-5-1); third term. Prerequisite: ME 35 ab recommended. Enrollment is limited and will be based on responses to a questionnaire available in the Registrar's Office during registration. Not offered on a pass/fail basis.* 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. Instructor: Staff.

ME 72 ab. Engineering Design Laboratory. *9 units (3-4-2), first term; (1-8-0), second term. Prerequisites: ME 35 abc, ME 71, Me 18 ab, CS 1 or equivalent, and instructor's permission. Enrollment is limited.* A project-based course in which teams of students design, fabricate, analyze, test, and operate an electromechanical device to compete against devices designed by other student teams. The class lectures and the projects stress the integration of mechanical design, sensing, engineering analysis, and computation to solve problems in engineering system design. The laboratory units of ME 72 can be used to fulfill a portion of the laboratory requirement for the ME or EAS option. Not offered on a pass/fail basis. Instructor: Staff.

ME 73. Machine Component Design. *9 units (3-4-2); second term. Prerequisites: ME 35 abc, ME 72, or instructor's permission.* Basic machine components, including bearings, seals, shafts, gears, belts, chains, couplings, linkages, and cams. Analysis and synthesis of these devices, as well as their use in the design of larger engineering systems, will be examined. The laboratory section makes use of contemporary mechanical hardware to provide students with "hands-on" experience with the components discussed in class. Not offered 2009–10.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or 18 units (2-15-1) third term.* For course description, see Computer Science.

ME 90 abc. Senior Thesis, Experimental. *9 units; (0-0-9) first term; (0-9-0) second, third terms. Prerequisite: 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: Lapusta.

ME 91 abc. Senior Thesis, Analytical. *9 units (0-0-9); first, second, third terms. Prerequisite: senior status; instructor's permission.* Undergraduate 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. Not offered on a pass/fail basis. Instructor: Lapusta.

ME 96. Mechanical Engineering Laboratory. *9 units (0-9-0); third term. Prerequisites: ME 18 ab, ME 19 ab, ME 35 ab.* A laboratory course with experiments drawn from diverse areas of mechanical engineering, including heat transfer, control, fluid mechanics, solid mechanics, atomic force microscopy, materials, combustion, turbomachinery, and dynamics. Instructor: Staff.

ME 100. Advanced Work in Mechanical Engineering. The faculty in mechanical engineering will arrange special courses on problems to meet the needs of qualified undergraduate students. Graded pass/fail for research and reading. A written report is required for each term.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aerospace.

E/ME 103. Management of Technology. *9 units (3-0-6).* For course description, see Engineering.

E/ME 105. Product Design for the Developing World. *9 units (3-0-6).* For course description, see Engineering.

EST/EE/ME 109 ab. Energy. *9 units(3-0-6.)* For course description, see Energy Science and Technology.

ME 110. Special Laboratory Work in Mechanical Engineering. *3–9 units per term; maximum two terms.* Special laboratory work or experimental research projects may be arranged by members of the faculty to meet the needs of individual students as appropriate. A written report is required for each term of work. Instructor: Staff.

ME 115 ab. Introduction to Kinematics and Robotics. *9 units (3-0-6); second, third terms. Prerequisites: Ma 2, ACM 95/100 ab recommended.* Introduction to the study of planar, rotational, and spatial motions with applications to robotics, computers, computer graphics, and mechanics. Topics in kinematic analysis will include screw theory, rotational representations, matrix groups, and Lie algebras. Applications include robot kinematics, mobility in mechanisms, and kinematics of open and closed chain mechanisms. Additional topics in robotics include path planning for robot manipulators, dynamics and control, and assembly. Course work will include laboratory demonstrations using simple robot manipulators. Instructor: Burdick.

ME 118. Thermodynamics. *9 units (3-0-6); first term. Prerequisites: ME 18 ab, ME 19 ab.* Fundamentals of classical and statistical thermodynamics. Basic postulates, thermodynamic potentials, chemical and phase equilibrium, phase transitions, and thermodynamic properties of solids, liquids, and gases. Taught concurrently with ChE/Ch 165. Instructor: Staff.

ME 119 ab. Heat and Mass Transfer. *9 units (3-0-6); second, third terms. Prerequisites: ME 18 ab, ME 19 ab, ACM 95/100 (may be taken concurrently).* Transport properties, conservation equations, conduction heat transfer, convective heat and mass transport in laminar and turbulent flows, phase change processes, thermal radiation. Instructor: Staff.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6).* For course description, see Aerospace.

ME/EST 122 ab. Sustainable Energy Engineering. *9 units (3-0-6); second, third terms. Prerequisites: ME 18 ab, ACM 95/100 (may be taken concurrently).* An in-depth examination of engineering systems to convert, store, transport, and use energy, with emphasis on technologies that reduce or eliminate dependence on fossil fuels and/or emission of greenhouse gases. Topics include thermodynamics of energy conversion, energy resources, stationary power generation (vapor power cycles, combined cycles, solar thermal systems, nuclear fission and fusion, solar photovoltaics, fuel cells, wind), carbon sequestration, alternative fuels (hydrogen, biofuels), and transportation systems (internal combustion engines, gas turbines, fuel cell and electric vehicles). The course will emphasize using quantitative methods to assess and compare different technologies. Taught concurrently with EST/EE/ME 109 ab. Instructor: Staff.

ME 131. Advanced Robotics: Manipulation and Sensing. *9 units (3-6-0); third term. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of robotic manipulation and sensing. Past topics have included advanced manipulator kinematics, grasping and dextrous manipulation using multifingered hands, and advanced obstacle avoidance and motion planning algorithms. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Instructor: Staff.

ME/CS 132. Advanced Robotics: Navigation and Vision. *9 units (3-6-0); second term. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of autonomous navigation and vision. Topics will include mobile robots, multilegged walking machines, use of vision in navigation systems. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Instructor: Staff.

ME 150 abc. Mechanical Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in applied mechanics and mechanical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Lapusta.

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.

MS/ME 162. Mechanical Behavior of Materials. *9 units (3-0-6).* For course description, see Materials Science.

AM/ME 165 ab. Elasticity. *9 units (3-0-6).* For course description, see Applied Mechanics.

ME 170. Introduction to Mechanical CAD. *4 units (1-0-3); third term.* An introduction to the use of one or more mechanical computer-aided design (CAD) packages via a series of weekly instructional exercises. Not offered 2009–10.

ME 171. Computer-Aided Engineering Design. *9 units (3-0-6); second term. Prerequisites: ACM 95/100 abc, ME 35 abc, ME 72, CS 1, or equivalent, working knowledge of the C computer programming language.* Methods and algorithms for design of engineering systems using computer techniques. Topics include the design process; interactive computer graphics; curves and surfaces (including cubic and B-splines); solid modeling (including constructive solid geometry and boundary models); kinematic and dynamic mechanism simulation; single and multivariable optimization; optimal design, and symbolic manipulation. Assessment of CAD as an aid to the design process. Not offered 2009–10.

ME 175. Fuzzy Sets in Engineering. *9 units (3-0-6); second term. Prerequisites: ACM 95/100 abc, working knowledge of the C computer programming language.* The relatively new mathematics of fuzzy sets has recently been used to represent and manipulate vague and imprecise information in engineering. This course will present the basics of fuzzy sets and fuzzy mathematics and explore applications in the areas of data representation; function representation; filters and triggers; engineering design and optimization, including (fuzzy) set-based concurrent engineering. Not offered 2009–10.

ME 200. Advanced Work in Mechanical Engineering. The faculty in mechanical engineering will arrange special courses on problems to meet the needs of graduate students. Graded pass/fail; a written report is required for each term of work.

ME 202 abc. Engineering Two-Phase Flows. *9 units (3-0-6). Prerequisites: ACM 95/100 abc, 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 2009–10.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

Ae/ACM/ME 232 ab. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ME/MS 260 abc. Micromechanics. *12 units (3-0-9). 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 2009–10.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Aerospace.

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.

MUSIC

Mu 10. Selected Topics in Music; *offered by announcement. Units to be determined by arrangement with instructor.* Instructors: Staff, visiting lecturers.

Mu 21. Understanding Music. *9 units (3-0-6); first term.* The Listening Experience I. How to listen to and what to listen for in classical and other musical expressions. Listening, analysis, and discussion of musical forms, genres, and styles. Course is intended for musicians as well as nonmusicians and is strongly recommended as an introduction to other music courses. Instructor: Neenan.

Mu 24. Introduction to Opera. *9 units (3-0-6); third term.* Opera exploded onto the cultural scene around the year 1600 and quickly became the most popular, expensive, and lavish spectacle in all of Europe. The course will trace the history of the genre examining masterpieces by Monteverdi, Handel, Mozart, Rossini, Verdi, Wagner, Strauss, Berg, and Britten, and will sample a host of newer works, including *Einstein on the Beach*, *The Death of Klinghoffer*, and *The Ghosts of Versailles*. Instructor: Staff.

Mu 25. History of Chamber Music. *9 units (3-0-6); third term.* To be coordinated with Caltech's spring chamber music performances; enrollment limited to students preparing performances of chamber music during the term. The course will survey the history of chamber music and will offer more in-depth exploration of works in preparation for performance. Not offered 2009–10.

Mu 26. Jazz History. *9 units (3-0-6); third term.* This course will examine the history of jazz in America from its roots in the unique confluence of racial and ethnic groups in New Orleans around 1900 to the present. The lives and music of major figures such as Robert Johnson, Jelly Roll Morton, Louis Armstrong, Benny Goodman, Duke Ellington, Count Basie, Charlie Parker, Dizzy Gillespie, Thelonius Monk, Miles Davis and others will be explored. Not offered 2009–10.

Mu 27. Fundamentals of Music Theory and Elementary Ear Training. *9 units (3-0-6); first term.* Basic vocabulary and concepts of music theory (rhythm and pitch notation, intervals, scales, function of key signatures, etc.); development of aural perception via elementary rhythmic and melodic dictation, and sight-singing exercises. Instructor: Neenan.

Mu 28. Harmony I. *9 units (3-0-6), second term. Prerequisite: Mu 27 or entrance exam.* Study of tonal harmony and intermediate music theory; techniques of chord progression, modulation, and melody writing according to common practice; ear training, continued. Instructor: Neenan.

Mu 29. Harmony II. *9 units (3-0-6), third term. Prerequisite: Mu 28 or entrance exam.* More advanced concepts of music theory, including chromatic harmony, and 20th-century procedures relating to selected popular music styles; ear training, continued. Instructor: Neenan.

Mu 122. Life and Music of Mozart. *9 units (3-0-6); second term.* This course will explore Mozart's music within the context of his life and times, including the early works composed as a child prodigy and touring artist; the first masterpieces he composed, and finally the masterworks written during his meteoric rise and his equally amazing fall from grace. Not offered 2009–10.

Mu 123. Life and Music of Beethoven. *9 units (3-0-6); third term.* The course will examine the exuberant works of Beethoven's youth, the series of grand, heroic masterpieces of the early 1800s, and the puzzling and mysterious works of his final decade. Not offered 2009–10.

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. Given in alternate years; not offered 2009–10.

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. Given in alternate years; not offered 2009–10.

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. Given in alternate years; not offered 2009–10.

PERFORMANCE AND ACTIVITIES

Courses under this heading cover the instructional content of a range of extracurricular activities and work in the fine arts and elsewhere. These courses will appear on the student's transcript, and will be graded pass/fail only. The units count toward the total unit requirement for graduation, but they do not count toward the 108-unit requirement in humanities and social sciences.

PA 15 abc. Student Publications. *3 units (1-0-2); first, second, third terms.* The elementary principles of newspaper writing and editing, with special attention to student publications at the Institute. Instructor: Staff.

PA 16 abc. Cooking Basics. *3 units (0-3-0); first, second, third terms.* The class will survey different cooking styles, techniques, and cuisines from around the world. Topics covered may include knives and tools; tastes and flavors; sauces and reductions; legumes, grains, and beans; meat; dessert. The emphasis will be on presentation and creativity. Instructor: Mannion.

PA 20 abc. Debate. *3 units (1-0-2); first, second, third terms.* Study and discussion of the annual intercollegiate debate topic. Instructor: Staff.

PA 30 abc. Guitar. *3 units (0-3-0); first, second, third terms.* Offered on three levels: beginning (no previous experience required), intermediate, and advanced. Instruction emphasizes a strong classical technique, including an exploration of various styles of guitar—classical, flamenco, folk, and popular. Instructor: Elgart.

PA 31 abc. Chamber Music. *3 units (0-3-0); first, second, third terms.* Study and performance of music for instrumental ensembles of two to eight members, and for piano four-hands. Literature ranges from the 16th to 21st centuries. Open to students who play string, woodwind, brass instruments, guitar, or piano. After auditioning, pianists will be placed in sections by the instructors. Section 1: Mixed ensembles. Instructor: D. Bing. Section 2: Piano four-hands. Instructor: Ward. Section 3: Guitar ensemble. Instructor: Elgart.

PA 32 abc. Symphony Orchestra. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for full symphony orchestra and chamber orchestra. The orchestra performs both the standard symphonic repertoire and contemporary music. Two and a half hours of rehearsal per week. Instructor: Gross.

PA 33 abc. Concert Band. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for the classical wind ensemble. Emphasis is placed on the traditional literature, but the study of contemporary music is an important part of the curriculum. Instructor: W. Bing.

PA 34 abc. Jazz Band. *3 units (0-3-0); first, second, third terms.* Study and performance of all styles of jazz, from Duke Ellington to Pat Metheny. Jazz improvisation is also stressed. Instructor: W. Bing.

PA 35 abc. Women's Glee Club. *3 units (0-3-0); first, second, third terms.* Performance of women's choral repertoire in all style periods, from the Renaissance to the present. Includes performances with orchestra and with the Men's Glee Club (singing mixed-voice repertoire). Includes opportunities for individual instruction. No previous experience required. Three hours a week. Instructor: LaVertu.

PA 36 abc. Men's Glee Club. *3 units (0-3-0); first, second, third terms.* Study and performance of TTBB and SATB choral music. Emphasis is placed on the traditional choral repertoire, including large works with orchestra, but the study of world folk music and popular music is also included. Includes performances with the Women's Glee Club. No previous experience is required. Instructor: LaVertu.

PA 37 abc. Chamber Singers. *3 units (0-3-0); first, second, third terms.* Advanced study and performance of SATB choral music. Emphasis is placed on more difficult choral repertoire, both a capella and accompanied. Includes performances with the glee clubs as well as at other on-campus events. Audition required. Participation in one of the glee clubs required. Instructor: LaVertu.

PA 40 abc. Theater Arts. *3 units (2-0-1); first, second, third terms.* Instruction in all phases of theatrical production, culminating in multiple performances for the public. A hands-on, practical approach includes workshops in stage combat, costume construction, scenic arts, occasional informal encounters with professional actors, designers, and directors. Understanding of dramatic structure, respect for production values, and problem solving are stressed. Material of academic value is drawn from 3,000 years of worldwide dramatic literature. Instructor: Brophy.

PA 61 abc. Silkscreen and Silk Painting. *3 units (0-3-0); first, second, third terms.* Instruction in silkscreen and airbrush techniques, using a variety of media including T-shirts. Instructor: Barry.

PA 62 abc. Drawing and Painting. *3 units (0-3-0); first, second, third terms.* Instruction in techniques of drawing and painting, utilizing models, architecture, and still lifes as subjects. Instructor: Barry.

PA 63 abc. Ceramics. *3 units (0-3-0); first, second, third terms.* Instruction in the techniques of creating ceramics, including the slab roller and potter's wheel, and glazing methods. Instructor: Freed.

PA 70 abc. Student-Taught Courses. *3 units (2-0-1); first, second, third terms.* A variety of subjects each term, taught by undergraduate students. Different subjects will fall under different section numbers. The courses offered each term will be decided based on student interest and a selection process by the Office of Student Affairs. More information at http://www.deans.caltech.edu/studenttaughtcourses.htm.

PA 80 abc. Pilot Training. *3 units (3-0-0); first, second, third terms*. A course designed for students interested in aviation who are considering a pilot's license. It will introduce the knowledge aspects of flying and prepare for the required FAA knowledge test. First term: private pilot topics. Second term: instrument flying. Third term: advanced topics (commercial flying, high-altitude flying, advanced systems, advanced weather, etc.). Instructors: Werntz, Areeda.

PHILOSOPHY

Hum/Pl 8. Right and Wrong. *9 units (3-0-6)*. For course description, see Humanities.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6).* For course description, see Humanities.

Pl 90 ab. Senior Thesis. *9 units (1-0-8).* Required of students taking the philosophy option. To be taken in any two consecutive terms of the senior year. Students will research and write a thesis of 10,000–12,000 words on a philosophical topic to be determined in consultation with their thesis adviser. Limited to students taking the philosophy option. Instructor: Staff.

Pl 98. Reading in Philosophy. *9 units (1-0-8). Prerequisite: Instructor's permission.* An individual program of directed reading in philosophy, in areas not covered by regular courses. Instructor: Staff.

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6); offered by announcement*. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or instructor's permission.

Pl 103. Medieval Philosophy. *9 units (3-0-6); third term.* This course examines the philosophy of Western Europe from the decline of pagan culture to the Renaissance, roughly 400–1400 C.E. Material covered will vary, but will likely include a thorough introduction to Late Greek neo-Platonic philosophy as background to reading figures such as Augustine, Boethius, Avicenna, Abailard, Averroes, Maimonides, Anselm, Albert the Great, Aquinas, Olivi, Scotus, and Ockham. Instructor: Manning.

HPS/Pl 120. Introduction to Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 122. Confirmation and Induction. *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 129. Introduction to Philosophy of Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 133. Philosophy and Neuroscience. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 136. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7).* For course description, see History and Philosophy of Science.

HPS/Pl 137. Experimental Philosophy. *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 150. 17th-Century Philosophy: Bacon to Leibniz. *9 units (3-0-6).* The course will examine the work of several prominent philosophers active during the so-called Century of Genius. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include the limits of human knowledge, the existence and nature of mind, matter, and God, and the relationship between science and philosophy. Philosophers discussed are selected from Bacon, Mersenne, Descartes, Gassendi, Hobbes, Digby, Spinoza, Malebranche, Arnauld, More, Cudworth, Locke, Newton, and Leibniz. Instructor: Manning.

Pl 151. 18th-Century Philosophy: Locke to Kant. *9 units (3-0-6).* The course will examine the work of several prominent philosophers active during the so-called Age of Enlightenment. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include ideas and perception, belief and knowledge, passion and reason, matter and mind, causation and free will, and the relationship between science and philosophy. Philosophers discussed are selected from Locke, Huygens, Leibniz, Newton, Wolff, Berkeley, Rousseau, Hume, Reid, and Kant. Instructor: Manning.

Pl/HPS 157. Leibniz vs. Newton: Philosophers at War. *9 units (3-0-6).*This course takes up a fascinating exchange between Leibniz and Newton, two towering figures at the dawn of modern physical science. It centers on the correspondence between Leibniz and Newton's disciple Samuel Clarke. Their letters (1714–1716) address foundational issues of 17th century dynamics: the existence of space and time; the architecture of matter; God and his agency in the world; miracles and laws of nature; free will and divine choice. A detailed overview of the scientific, philosophical, and religious background to the debate will serve to introduce the debate. Instructor: Stan.

HPS/Pl 169. Selected Topics in Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Pl/HPS 183. Bioethics. *9 units (3-0-6); offered by announcement.* A survey of issues in bioethics. Topics may include reproduction and cloning, stem-cell research, organ transplantation and sale, informed consent, killing vs. letting die, cure vs. enhancement, and research ethics. Instructor: Cowie.

Pl/HPS 184. Science, Ethics, and Public Policy. *9 units (3-0-6); offered by announcement.* This course discusses some moral and social issues concerning research in the sciences (chiefly, biomedicine, with special attention to stem-cell research.) We will begin by discussing attempts to find a framework within which the issues can be addressed, and then we will discuss some specific topics. In most cases we will not so much seek answers to moral questions as attempt to identify helpful questions, clarify the issues involved, and analyze the moral status of the protagonists. We will also pay special attention to issues of public policy, and ask how scientific research should be organized and funded in a democracy. Not offered 2009–10.

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 2009–10.

Pl 186. Political Philosophy. *9 units (3-0-6); offered by announcement.* This course will address one or more issues in contemporary political theory and/or the history of political thought. Topics may include the nature of democracy; liberalism; distributive justice; human rights; the moral and legal regulation of warfare; the status of positive law; social choice theory; the relations between the market and the state. The work of figures such as Plato, Aristotle, Locke, Hobbes, Mill, Machiavelli, and Rawls will be discussed. Not offered 2009–10.

Pl 187. Natural Justice. *9 units (3-0-6); third term.* This course examines the unorthodox view that morality is a natural phenomenon—the product of a combination of biological and cultural evolution. It reviews and criticizes the traditional arguments used to deny both moral naturalism and moral relativism, notably the Naturalistic Fallacy. It assesses the success of the approach advocated by evolutionary biologists and psychologists. It examines the evidence from laboratory experiments on fairness and justice. Finally, it attempts to synthesize all these strands using the theory of games as a unifying framework. Instructor: Staff.

PHYSICAL EDUCATION

PE 1 abc. Student Designed Fitness. *3 units. May only be used for 3 units of the 9-unit physical education requirement.* Independent fitness program as arranged with instructor, three times a week. Detailed proposals must be submitted in writing during first week of each term. Instructor: D'Auria.

PE 2 abc. Skin Diving. *3 units.* Fundamentals of skin diving and oceanography. Instructor: Dodd.

PE 4 abc. 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: Levesque.

PE 6 abc. Core Training, Beginning/Intermediate. *3 units.* Learn to develop functional fitness using core stability training techniques that focus on working the 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 abc. Speed and Agility Training, Intermediate/Advanced. *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 the development of an individual or sport-specific training workout will be taught. Instructor: Staff.

PE 8 abc. Fitness Training, Beginning. *3 units.* An introductory class 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 then be able to design an exercise program for lifelong fitness. Instructor: Staff.

PE 9 abc. Soccer. *3 units.* Fundamental instruction on shooting, passing, trapping, dribbling, penalty kicks, offensive plays, defensive strategies, and goal keeping. Class includes competitive play using small field and full field scrimmages. Instructor: Uribe.

PE 10 abc. Aerobic Dance. *3 units.* Each class includes a thorough warm-up, a cardiovascular workout phase that also 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 12 abc. Baseball Skills, Intermediate/Advanced. *3 units.* Baseball skills—including infield/outfield, pitcher/catcher, and batting drills—taught, leading to competitive play. Students must have experience in hard ball. Instructor reserves the right to exclude students who do not fit criteria. Instructor: D'Auria.

PE 14 abc. Basketball Skills, Beginning and Beginning/Intermediate. *3 units.* Features fundamental instruction on shooting, dribbling, passing, defensive positioning, and running an offense. Class includes competitive play and free-throw shooting. Instructors: Eslinger, Marbut.

PE 20 abc. Fencing, Beginning and Intermediate/Advanced. *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. Intermediate/Advanced covers foil theory and techniques, group drillwork, and video analysis. Instructor: Staff.

PE 23 abc. Track and Field, Beginning. *3 units.* Features instruction on 10 different track events, allowing the student an opportunity to attempt a variety of skills: shot put, discus, javelin, sprints, hurdles, long jump, high jump, middle- and long-distance running, and the relays. Class emphasis placed on learning new skills safely with time devoted to warm-up and stretching, as well as weight training for specific events. Instructor: Levesque.

PE 24 abc. Yoga, Beginning. *3 units.* 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 the chance of athletic injury. Instructor: Staff.

PE 27 abc. Ultimate Frisbee. *3 units.* Instruction will center on developing students' knowledge of techniques, rules, strategy, etiquette, and safety regulations of the game. Students will develop the ability to perform all the skills necessary to play the game confidently on a recreational basis. Instructor: Staff.

PE 30 abc. Golf, Beginning, Intermediate, and Advanced. *3 units.* Beginning class 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 class will focus on swing development of specialty shots and on course play management. Advanced instruction covers course management and mental aspects of performance. Instructor: Staff.

PE 35 abc. Diving, Beginning/Intermediate. *3 units.* Teaches the fundamentals of springboard diving to include basic approach, and five standard dives. Intermediate class includes instruction in the back somersault, forward somersault, forward somersault full twist, and reverse somersault. Instructor: Dodd.

PE 36 abc. Swimming, Beginning/Intermediate and Advanced. *3 units.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Advanced class focuses on proper technique of the four competitive strokes using video and drills along with instruction on training methods and proper workout patterns. Instructor: Dodd.

PE 38 abc. Water Polo. *3 units.* Basic recreational water polo with instruction of individual skills and team strategies. A background in swimming is encouraged. Instructor: Staff.

PE 40 abc. Dance Dance Revolution. *3 units.* Dance-rhythm game emphasizing speed and accuracy of footwork. Basic skills in rhythm and coordination will be taught and developed with play. Intermediate instruction will expand on these skills and focus on higher-level techniques and stamina. Instructor: Staff.

PE 44 abc. Karate (Shotokan), Beginning and Intermediate/ Advanced. *3 units.* 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 abc. 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 abc. T'ai-Chi Ch'uan, Beginning and Intermediate/ Advanced. *3 units.* Chinese movement art emphasizing relaxation and calm awareness through slow, flowing, meditative movement using only the minimum of strength needed to accomplish the action. Instructor: Staff.

PE 50 abc. Badminton, Beginning/Intermediate. *3 units.* 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, service 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 abc. Racquetball, Beginning and Intermediate/Advanced. *3 units.* Fundamentals of the game will be emphasized, including rules, scoring, strategy, and winning shots. All types of serves will be covered, as well as a variety of shots to include kill, pinch-off, passing, ceiling, and off-the-backwall. Singles and doubles games will be played. Intermediate/Advanced course will review all fundamentals with a refinement of winning shots and serves and daily games. Instructor: Staff.

PE 56 abc. Squash, Beginning, Intermediate, Advanced. *3 units.* Learn by playing as the 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 classes will concentrate on skill development with the inclusion of forehand and backhand drives, lobs, volleys, and drops, with an emphasis on court movement, shot selection, and tactics. Instructor: Staff.

PE 60 abc. Tennis, Beginning, Intermediate, and Advanced. *3 units.* Stroke fundamentals, singles and doubles play, plus rules, terminology, and etiquette are covered in all classes. Beginning class emphasizes groundstrokes, volleys, serve, and grips. Beginning/Intermediate class is for those players caught between levels and will concentrate on strategy, drills, and match play. Intermediate level focuses on improving technique, footwork, and court positioning, with instruction on approach shots, volleys, overheads, and lobs. Advanced course fine tunes each individual's skills while targeting weaknesses. Instructors: D'Auria, Gamble, Uribe.

PE 70 abc. Weight Training, Beginning/Intermediate. *3 units.* Active participation in a strength and conditioning program designed for individual skill level and desired effect. Course will enlighten students on various methods, terminology, and techniques in the areas of isokinetic strength and cardiovascular fitness training. Instructor: Staff.

PE 77 abc. Volleyball, Beginning, Intermediate, and Advanced. *3 units.* Fundamental instruction on drills, strategies, and rules, with game-playing opportunity. Basics of serve, pass, set, spike, defense, and court position will be taught. Intermediate level focuses on skill development to a more competitive standard and features multiple offenses and understanding officiating. Advanced class emphasizes specialization of all skills, court position, and multiple offenses and defenses. Instructor: Staff.

PE 80 abc. Health Advocates. *3 units (1-1-1); first, second, third terms.* A course designed to involve students with health care and education, develop familiarity with common college health problems, and provide peer health services on and off campus. First term: CPR and first aid certification and basic anatomy and physiology. Second and third terms: lectures and discussions on current student and community health problems, symptoms, and treatment. Each student will be expected to devote one hour per week to a supervised clinical internship at the Health Center. *Does not satisfy the Institute physical education requirement.* Instructor: Staff.

PE 82 abc. Rock Climbing, Beginning and Intermediate. *3 units.* 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. Skills will be demonstrated and practiced on a climbing wall and then later at an off-campus climbing site. Intermediate level will include ascents on prussiks or jumars, with more off-campus climbing. Instructor: Staff.

PE 84 abc. Table Tennis, Beginning, Intermediate, and Advanced. *3 units.* Introductory course to provide general knowledge of equipment, rules, and basic strokes, including topspin drive, backspin chop, and simple block in both forehand and backhand. Multiball exercise utilizing robot machines and video. Intermediate class covers regulations for international competition and fundamentals of winning table tennis, including footwork drills, smash, serve, and attack. Instructor: Staff.

Intercollegiate Teams

PE 83 abc. Intercollegiate Basketball Team (Women). *3 units.* Coach: Marbut.

PE 85 abc. Intercollegiate Track and Field Team (Men and Women). *3 units.* Coach: Levesque.

PE 87 abc. Intercollegiate Swimming Team (Men and Women). *3 units.* Coach: Dodd.

PE 89 abc. Intercollegiate Fencing Team (Men and Women). *3 units.* Coach: D'Asaro.

PE 90 abc. Intercollegiate Water Polo Team (Men and Women). *3 units.* Coach: Moser.

PE 91 abc. Intercollegiate Basketball Team (Men). *3 units.* Coach: Eslinger.

PE 92 abc. Intercollegiate Soccer Team (Men). *3 units.* Coach: Uribe.

PE 93 abc. Intercollegiate Baseball Team (Men). *3 units.* Coach: D'Auria.

PE 95 abc. Intercollegiate Tennis Team (Men). *3 units.* Coach: Gamble.

PE 96 abc. Intercollegiate Tennis Team (Women). *3 units.* Coach: Gamble.

PE 97 abc. Intercollegiate Cross-Country Team (Men and Women). *3 units.* Coach: Jung.

PE 99 abc. Intercollegiate Volleyball Team (Women). *3 units.* Coach: Colon.

PHYSICS

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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: Zmuidzinas, McKeown, Politzer.

Ph 2 ab. Waves, Quantum Mechanics, and Statistical Physics. *9 units (4-0-5); first, second terms. Prerequisites: Ph 1 abc, Ma 1 abc, or equivalents.* The second year of a five-term introductory course in classical and modern physics. Topics to be covered include waves and introductory quantum mechanics first term, statistical physics second term. Instructors: Martin, Kamionkowski, Filippone.

Ph 3. Physics Laboratory. *6 units; first, second, third terms. Prerequisite: Ph 1 a or instructor's permission.* An introduction to experimental technique, commonly used in the physical sciences. A variety of topics is presented, including the Maxwell top, electrical and mechanical resonant systems, and radioactivity. Special emphasis is given to data analysis techniques based on modern statistical methods. The course consists of one three-hour laboratory session a week, conferences with the instructor, prelaboratory preparation, and analysis of experimental results. Graded pass/fail; seniors receive letter grades. Only one term may be taken for credit. Instructors: Sannibale, Adhikari.

Ph 5. Physics Laboratory. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents.* A laboratory course dealing with "operational" electronics with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes, and transistors. Combining diodes, transistors, and operational amplifiers; computer data acquisitions. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Sannibale, Adhikari.

Ph 6. Physics Laboratory. *9 units; second term. Prerequisites: Ph 1 abc, Ph 2 b or Ph 12 b (or taken concurrently), and Ph 3 or equivalent.* Experiments in electromagnetic phenomena such as electromagnetic induction, properties of magnetic materials, and high-frequency circuits. Mobility of ions in gases; precise measurement of the value of e/m of the electron. Instructors: Rice, Sannibale, Adhikari.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisite: Ph 6 or equivalent.* Experiments in atomic and nuclear physics, including studies of the Balmer series of hydrogen and deuterium, the decay of radioactive nuclei, absorption of X rays and gamma rays, ratios of abundances of isotopes, and the Stern-Gerlach experiment. Instructors: Rice, Sannibale, Adhikari.

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: Politzer.

Ph 10. Frontiers in Physics. *3 units (2-0-1); first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the physics department or a visitor, to discuss his or her research at an introductory level; the other class meetings will be used to explore background material related to seminar topics and to answer questions that arise. The course will also help students find faculty sponsors for individual research projects. Graded pass/fail. Instructor: Soifer.

Ph 11 abc. Research Tutorial. *6 units (2-0-4); second and third terms of freshman year and first term of sophomore year.* A small number of students will be offered the opportunity to enroll in this tutorial, the purpose of which is to demonstrate how research ideas arise, and are evaluated and tested, and how those ideas that survive are developed. This is accomplished by doing individual, original projects. There will be weekly group meetings and individual tutorial meetings with the instructor. Support for summer research at Caltech between the freshman and sophomore years will be automatic for those students making satisfactory progress. Graded pass/fail. Instructor: Tombrello.

Ph 12 abc. Waves, Quantum Physics, and Statistical Mechanics. *9 units (4-0-5); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, or equivalents.* A one-year course primarily for students intending further work in the physics option. Topics include classical waves; wave mechanics, interpretation of the quantum wave-function, one-dimensional bound states, scattering, and tunneling; thermodynamics, introductory kinetic theory, and quantum statistics. Instructors: Kimble, Preskill.

Ph 20, 21, 22. Computational Physics Laboratory. A series of courses on the application of computational techniques to simulate or solve simple physical systems, with the intent of aiding both physics understanding and programming ability. Instructors: Mach, Prince.

20. *6 units (0-6-0); first, second, third terms.* Introduction to scientific computing with applications to physics. Use of numerical algorithms and symbolic manipulation packages for solution of physical problems. Numerical integration and numerical solution of differential equations of motion. Simulation of orbital mechanics.

21. *6 units (0-6-0); second, third terms. Prerequisite: Ph 20 or equivalent experience with programming and numerical techniques.* Introduction to numerical algorithms for scientific computing. Root-finding, Runge-Kutta methods, Monte Carlo techniques, numerical solution of partial differential equations, minimization techniques such as neural networks. Applications to problems in classical mechanics and discrete-element electromagnetism.

22. *6 units (0-6-0); third term. Prerequisite: Ph 20 or equivalent experience with programming and numerical techniques.* Introduction to scientific computing on parallel computers. Introduction to parallel computing and multiprocessing. Message passing on networked workstations. Algorithm decomposition and parallelization. Numerical solution of N-body systems on multiprocessor computers.

Ph 70. Oral and Written Communication. *6 units (2-0-4); first, second terms.* Provides practice and guidance in oral and written communication of material related to contemporary physics research. Students will choose a topic of interest, make presentations of this material in a variety of formats, and, through a guided process, draft and revise a technical or review article on the topic. The course is intended for senior physics majors. *Fulfills the Institute scientific writing requirement.* Instructor: Hitlin.

Ph 77 abc. Advanced Physics Laboratory. *9 units (0-5-4); first, second, third terms. Prerequisite: Ph 7 or instructor's permission.* A three-term laboratory course to familiarize students with equipment and procedures used in the research laboratory. Experiments illustrate fundamental physical phenomena in atomic, optical, condensed-matter, nuclear, and particle physics, including NMR, laser-based atomic spectroscopy, gamma and X-ray spectroscopy, muon decay, weak localization, superconductivity, positron annihilation, and others. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: To register for this course the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, the student's thesis adviser. Laboratory work is required for this course. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note, below.

Ph 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: To register for this course the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note, below.

Note: Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the chair of the Physics Undergraduate Committee, or any other member of this committee. A grade will not be assigned in Ph 78 or Ph 79 until the end of the third term. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ph 101. Order-of-Magnitude Physics. *9 units (3-0-6); third term.* Emphasis will be on using basic physics to understand complicated systems. Examples will be selected from properties of materials, geophysics, weather, planetary science, astrophysics, cosmology, biomechanics, etc. Not offered 2009–10.

Ph 103 ab. Topics in Contemporary Physics. *9 units (3-0-6); first, second terms. Prerequisite: instructor's permission.* A series of introductory one-term, independent courses. Students may register for any particular term or terms.

a. Atomic and Molecular Spectroscopy. *Second term.* This course will review the basic spectroscopy of atoms and molecules, with applications to astrophysics, the terrestrial atmosphere, and the laboratory. Species to be discussed include hydrogen and simple multielectron atoms such as carbon, diatomic and polyatomic molecules, and some solids. Mechanisms and effects determining linewidths and lineshapes will be discussed for laboratory, atmospheric, and astrophysical conditions. Instructor: Phillips.

Ph/Bi 103 b. Neuroscience for Physicists and Engineers. *First term.* A reading and discussion course on topics ranging from the function of single neurons to methods for studying multineural activity in synapses; electrical recording; vision; positron and NMR topography; and neural modeling. Preference is given to physics seniors. Instructor: Pine.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6).* For course description, see Astrophysics.

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (the take-home lab of Ph 1 bc may be substituted for Ph 3).* A laboratory course dealing with "operational" electronics with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes, and transistors. Combining diodes, transistors, and operational amplifiers; computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Sannibale, Adhikari.

Ph 106 abc. Topics in Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 ab or Ph 12 abc, Ma 2.* An intermediate course in the application of basic principles of classical physics to a wide variety of subjects. Roughly half of the year will be devoted to mechanics, and half to electromagnetism. Topics include Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, boundary-value problems, multipole expansions, and various applications of electromagnetic theory. Instructors: Cross, Eisenstein.

APh/Ph 115 ab. Physics of Transport in Fluids. *9 units (3-0-6).* For course description, see Applied Physics.

Ph/EE 118 ab. Low-Noise Electronic Measurement. *9 units (3-0-6); first, second terms. Prerequisite: Ph 105 or equivalent.* An introduction to ultralow-noise electrical measurements and sensor technology as applied to experimental research. Topics include physical noise processes, signal transduction, synchronous and lock-in detection, digital signal transforms, and other aspects of precision measurements. Specific sensor technologies will include SQUID sensors, single electron transistors, transition-edge sensors, tunnel junction detectors, micro- and nanomechanical detectors, and biosensors. Instructor: Roukes.

Ph 125 abc. Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 ab, Ph 12 abc or Ph 2 ab, or equivalents.* A one-year course in quantum mechanics and its applications, for students who have completed Ph 12 or Ph 2. Wave mechanics in 3-D, scattering theory, Hilbert spaces, matrix mechanics, angular momentum, symmetries, spin-$^1/_2$ systems, approximation methods, identical particles, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructor: Wise.

Ph 127 abc. Statistical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 12 c or equivalent, and a basic understanding of quantum and classical mechanics.* A course in the fundamental ideas and applications of classical and quantum statistical mechanics. Topics to be covered include the statistical basis of thermodynamics; ideal classical and quantum gases (Bose and Fermi); lattice vibrations and phonons; weak interaction expansions; phase transitions; and fluctuations and dynamics. Instructor: Motrunich.

Ph 129 abc. Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc and ACM 95/100 abc or Ma 108 abc, or equivalents.* Mathematical methods and their application in physics. First term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. Second term covers group theoretic methods in physics. Third term focuses on probability and statistics in physics. The three terms can be taken independently. Instructors: Porter, Ooguri.

Ph 134. String Theory. *9 units (3-0-6); third term. Prerequisites: Ph 125 ab, Ph 106 ab.* A basic course in string theory designed to be accessible to a broad audience. The main topics include the motion of relativistic point particles and strings, actions, world-sheet symmetries and currents, light-cone quantization, and the spectra of relativistic open and closed strings. The course will conclude with an exploration of D-branes, T-duality, or string thermodynamics, depending on student interest. Not offered 2009–10.

Ph 135 abc. Applications of Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 abc or equivalent.* Applications of quantum mechanics to topics in contemporary physics. Particle physics, quantum optics, and nuclear physics will be offered first, second, third terms, respectively. Terms may be taken independently. Instructors: Weinstein, Kimble, Filippone.

Ph 136 abc. Applications of Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: 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. Not offered 2009–10.

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. Graded pass/fail.

Ph 172. Research in Experimental Physics. *Units in accordance with work accomplished.* Approval of the student's research supervisor and department adviser must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics. *Units in accordance with work accomplished.* Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6).* For course description, see Bioengineering.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph 199. Frontiers of Fundamental Physics. *9 units (3-0-6); second term. Prerequisite: Ph 125 abc, Ph 106 abc.* This course will explore the frontiers of research in particle physics and cosmology. In 2010, the focus will be on particle physics at the high-energy frontier (the Large Hadron Collider and the International Linear Collider). Topics include the origin of mass (spontaneous symmetry breaking, the Higgs); supersymmetry, dark matter candidates, extra dimensions, grand unification, and physics at the Planck scale. The course is geared towards seniors and first-year graduate students who are not in particle physics, although students in particle physics are welcome to attend. Instructors: Spiropulu, Weinstein.

Ph 205 abc. Relativistic Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: 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. Instructor: Kapustin.

Ph 210. Theoretical Quantum Chromodynamics. *9 units (3-0-6); third term. Prerequisite: Ph 205 ab.* Applications of quantum field theory to quantum chromodynamics, including operator product expansion, twist expansion and applications to deep inelastic scattering and Drell-Yan; effective field theories, including chiral perturbation theory, heavy quark effective theory, and soft collinear effective theory; large Nc; introduction to lattice chromodynamics. Applications to strong interaction phenomenology and weak decays. Not offered 2009–10.

Ph 217 abc. Introduction to the Standard Model. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 abc and Ph 236 abc, or equivalent.* This course deals with 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. In the second half of the course, the standard picture for cosmology is discussed. The predictions of inflation for the primordial density perturbations are reviewed. The microwave background anisotropy is discussed. Not offered 2009–10.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 129 abc or equivalent.* The theory of quantum information and quantum computation. Overview of classical information theory, compression of quantum information, transmission of quantum information through noisy channels, quantum error-correcting codes, quantum cryptography and teleportation. Overview of classical complexity theory, quantum complexity, efficient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructor: Kitaev.

Ph/APh 223 abc. Advanced Condensed-Matter Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent, or instructor's permission.* Advanced topics in condensed-matter physics, emphasizing the application of formal quantum field theory and group theory methods to many-body systems. Selected topics may include path integral and canonical formalisms, Green's function techniques and Feynman diagrams, Fermi liquid theory, Luttinger liquid theory, symmetry breaking and Landau-Ginzburg theory of phase transitions, group theory and its applications, field theory for interacting bosons and superfluidity, superconductivity, Kondo effect, Hubbard and t-J models, gauge theory, fractional quantum Hall effect, anyons, and topological field theory. Instructors: Yeh, Refael.

Ph 229 abc. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 129 abc or equivalent.* Advanced topics in geometry and topology that are widely used in modern theoretical physics. Emphasis will be on understanding and applications more than on rigor and proofs. First term will cover basic concepts in topology and manifold theory. Second term will include Riemannian geometry, fiber bundles, characteristic classes, and index theorems. Third term will include anomalies in gauge-field theories and the theory of Riemann surfaces, with emphasis on applications to string theory. Not offered 2009–10.

Ph 230 abc. Elementary Particle Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 abc or equivalent.* Advanced methods in quantum field theory. First term: introduction to supersymmetry, including the minimal supersymmetric extension of the standard model, supersymmetric grand unified theories, extended supersymmetry, supergravity, and supersymmetric theories in higher dimensions. Second and third terms: nonperturbative phenomena in non-Abelian gauge field theories, including quark confinement, chiral symmetry breaking, anomalies, instantons, the 1/N expansion, lattice gauge theories, and topological solitons. Instructor: Gukov.

Ph 231 abc. Elementary Particle Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent.* An introduction to elementary particle physics, stressing experimental phenomena and their theoretical interpretations. The standard model and its confrontation with experiment will be covered. Current notions for particle physics beyond the standard model will be explored, along with possible experimental signatures. Experimental techniques will also be discussed, including an introduction to accelerator physics. Not offered 2009–10.

Ph 232. Introduction to Topological Field Theory. *9 units (3-0-6); first term. Prerequisite: Ph 205.* Topological field theories are the simplest examples of quantum field theories which, in a sense, are exactly solvable and generally covariant. During the past twenty years they have been the main source of interaction between physics and mathematics. Thus, ideas from gauge theory led to the discovery of new topological invariants for 3-manifolds and 4-manifolds. By now, topological quantum field theory (TQFT) has evolved into a vast subject, and the main goal of this course is to give an accessible introduction to this elegant subject. Instructor: Ooguri.

Ph 235 abc. Introduction to Supersymmetry and String Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205.* First term: introduction to supersymmetry. After explaining the basic concepts of supersymmetry, the emphasis will be on formulating and analyzing the minimal supersymmetric extension of the standard model and supersymmetric grand unified theories. There will also be brief introductions to supersymmetric theories in higher dimensions, theories with extended supersymmetry, and supergravity. Second term: introduction to superstring theory. Topics to be discussed include relativistic strings and their quantization, perturbative string theory, low energy effective supergravity theories, p-brane solutions and p-brane world volume theories, compactification of extra dimensions, M theory and F theory, dualities relating various superstring and M theory configurations, problems and prospects. Not offered 2009–10.

Ph 236 abc. Relativity. *9 units (3-0-6); first, second, third 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. Instructor: Chen. In 2009–10, offered first and second terms only.

Ph 237. Gravitational Waves. *9 units (3-0-6); third term. Prerequisite: Ph 236 a.* The theory and astrophysical phenomenology of gravitational-wave sources (black holes, neutron stars, compact binaries, early-universe phenomena, etc.). Gravitational-wave detectors (LIGO, LISA, and others), and data analysis. Instructor: Adhikari.

Ph 242 ab. Physics Seminar. *3 units (2-0-1); first, second terms.* Topics in physics emphasizing current research at Caltech. One two-hour meeting per week. Speakers will be chosen from both faculty and students. Registration restricted to first-year graduate students in physics; exceptions only with permission of instructor. Graded pass/fail. Instructor: Stone.

Ph 250 abc. Introduction to String Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 or equivalent.* The first two terms will focus largely on the bosonic string. Topics covered will include conformal invariance and construction of string scattering amplitudes, the origins of gauge interactions and gravity from string theory, T-duality, and D-branes. The third term will cover perturbative aspects of superstrings, supergravity, various BPS branes, and string dualities. Instructor: Schwarz.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 or Ph 173 when the student has progressed to the point where research leads directly toward the thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

POLITICAL SCIENCE

PS 12. Introduction to Political Science. *9 units (3-0-6); first, second, 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: Kiewiet, Ordeshook.

PS 99 ab. Political Science Research Seminar. *9 units (3-0-6). Prerequisite: 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.*

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); first 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. Instructor: Alvarez.

PS 121. Congressional Policy Formation and Legislative Process. *9 units (3-0-6).* Decision making in legislative bodies, with emphasis on the United States Congress. An investigation into the impact of congressional structure and practices on the policies adopted by the federal government. Not offered 2009–10.

PS 122. Political Representation. *9 units (3-0-6); second term. Prerequisite: PS 12.* Theory, practice, and consequence of political representation in the electoral context. Topics include the concept of representation; how the degree of representation of various groups and interests (such as ethnic and racial) is affected by different electoral rules; and the impact of representation of minorities on public policies. The primary focus is on the empirical literature pertaining to the United States, but examples from other countries are also examined for comparative purposes. Instructor: Ueda.

PS 123. Regulation and Politics. *9 units (3-0-6); first term. Prerequisite: PS 12.* This course will examine the historical origins of several regulatory agencies and trace their development over the past century or so. It will also investigate a number of current issues in regulatory politics, including the great discrepancies that exist in the cost-effectiveness of different regulations, and the advent of more market-based approaches to regulations instead of traditional "command-and-control." Not offered on a pass/fail basis. Instructor: Kiewiet.

PS 124. Political Economy. *9 units (3-0-6); second term.* The aim of this course is to introduce students to theoretical and applied research in political economy. The focus will be on formal analysis of the strategic interaction between rational individuals, political institutions, and economic outcomes. Some of the questions will be: Why do people vote? What are the incentives of elected politicians, and what is the effect of these incentives on the policies they will implement? To what extent do differences in political institutions account for differences in redistributive policies? Topics may include the theory of voting, models of direct democracy, models of electoral competition, the political economy of redistribution, and comparative political institutions. Instructor: Mattozzi.

BEM/PS 126. Business and Public Policy. *9 units (3-0-6).* For course description, see Business Economics and Management.

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 2009–10.

PS 132. Formal Theories in Political Science. *9 units (3-0-6). Prerequisite: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theoretic and social choice models and models of political processes based on them. Instructor: Ordeshook.

PS 135. Analyzing Legislative Elections. *9 units (3-0-6); second term.* The purpose of this course is to understand legislative elections. The course will study, for example, what role money plays in elections and why incumbents do better at the polls. It will also examine how electoral rules impact the behavior both of candidates and voters, and will explore some of the consequences of legislative elections, such as divided government. Instructor: Katz.

PS/SS 139. Comparative Politics. *9 units (3-0-6). Prerequisite: PS 12 or SS 13.* The politics of non-American political systems. Areas of study: the politics of nondemocratic states, including the Communist nations; the politics of developing societies; the politics of the Western European democracies. Emphasis on the effect of distinctive institutions on the performance of government and the content of public policy. Not offered 2009–10.

PS 141. A History of Budgetary Politics in the United States. *9 units (3-0-6); offered by announcement.* 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); first term. Prerequisite: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theory models in social science. Axiomatic utility theory and general noncooperative games. Instructor: Echenique.

PS/Ec 173. Cooperation and Social Behavior. *9 units (3-0-6). Prerequisite: PS/Ec 172 or instructor's permission.* Game theoretic and evolutionary approaches to modeling various types of cooperative, altruistic, and social behavior. Emphasis on economic and political applications. Not offered 2009–10.

Ec/PS 190. Undergraduate Research. *Units to be arranged.* For course description, see Economics.

PSYCHOLOGY

Psy 15. Social Psychology. *9 units (3-0-6); offered by announcement.* The study of how people think about other people and behave toward or around others. Topics include attribution, social cognition, motivation and incentive, social influence, liking, stereotyping, deception, fairness and altruism, and conformity. Instructor: Castelli.

Psy 16. Understanding Psychological Disorders. *9 units (3-0-6); first term.* A descriptive and theoretical survey of the major forms of psychopathology in children, adolescents, and adults. The course will examine current trends and research in the fields of mental health and psychopathology. Instructor: Castelli.

Psy 20. Introduction to Cognitive Psychology. *9 units (3-0-6); second term.* This course will develop basic concepts in how humans process different kinds of information such as visual, auditory, and symbolic. These concepts will then be used to explore topics such as visual perception, attention and automaticity, working and long-term memory, imagery, knowledge representation, language acquisition and comprehension, judgement and choice, reasoning and decision making, problem solving, and group differences. Instructor: Spezio.

Psy 25. Reading and Research in Psychology. *Units to be determined by the instructor.* Written report required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.* Not offered 2009–10.

Psy 101. Selected Topics in Psychology. *Units to be determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units*. For course description, see Computation and Neural Systems.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Psy 125. Reading and Research in Psychology. Same as Psy 25, but for graduate credit. *Not available for credit toward humanities–social science requirement.*

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 2009–10.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi/CNS/Psy 133. Neurobiology and Evolution of Emotion: Do Flies Have Feelings? *9 units (3-0-6).* For course description, see Biology.

SS/Psy/Bi/CNS 140. Social Neuroscience. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

SOCIAL SCIENCE

SS 13. The Application of Social Scientific Methods to Problems in History. *9 units (3-0-6); first term.* The application of theory from economics, political science, and demography to historical subjects, with an emphasis on questions of institutional change. The historical topics covered will depend upon the instructor. Not offered 2009–10.

BEM/Ec/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4).* For course description, see Business Economics and Management.

SS 98. Reading in Social Science. *Units to be determined for the individual by the department. Elective, in any term.* Reading in social science and related subjects, done either in connection with the regular courses or independently of any course, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

SS 101. Selected Topics in Social Science. *9 units (3-0-6); offered by announcement.* Not available for social science credit unless specifically approved by social science faculty. Instructors: Staff, visiting lecturers.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units.* For course description, see Computation and Neural Systems.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6).* For course description, see History.

Ec/SS 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 Industrial Revolution. *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.

SS/Psy/Bi/CNS 140. Social Neuroscience. *9 units (3-0-6); third term. Prerequisite: Bi/CNS 150 recommended.* This course will survey the neural basis of social behavior, drawing on both theoretical and empirical approaches. Recent findings from cognitive neuroscience will be discussed, with an emphasis on data from humans. Topics will include motivation, emotion, theory of mind, social perception, and simulation. Not offered 2009–10.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6).* For course description, see Anthropology.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

The graduate courses listed below are not necessarily taught each year. They will be offered as need dictates.

SS 200. Selected Topics in Social Science. *Units to be determined by arrangement with instructors; offered by announcement.* Instructors: Staff, visiting lecturers.

SS 201 abc. Analytical Foundations of Social Science. *9 units (3-0-6); first, second, third terms.* This course covers the fundamentals of utility theory, game theory, and social choice theory. These basic theories are developed and illustrated with applications to electoral politics, market trading, bargaining, auctions, mechanism design and implementation, legislative and parliamentary voting and organization, public economics, industrial organization, and other topics in economics and political science. Instructors: Echenique, Chambers, Palfrey.

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. Instructors: Alvarez, Ordeshook, Katz.

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. Instructors: Border, Echenique, Ledyard.

SS 209. Behavioral Economics. *9 units (3-0-6); offered by announcement. 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). 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: Mattozzi, Iaryczower, Yariv.

SS 211 abc. Advanced Economic Theory. *9 units (3-0-6); first, second, third terms. May be repeated for credit.* Advanced work in a specialized area of economic theory, with topics varying from year to year according to the interests of students. Instructors: Palfrey, Chambers.

SS 212. Application of Microeconomic Theory. *9 units (3-0-6). May be repeated for credit.* A working seminar in which the tools of microeconomic theory are applied to the explanation of events and the evaluation of policy. Not offered 2009–10.

SS 213 abc. Financial Economics. *9 units (3-2-4); first, second, third terms.* First term: asset pricing theory, statistical tests on historical data and evidence from financial markets experiments. Second term: financial econometrics, with emphasis on applications to risk management. Third term: general equilibrium foundations of asset and option pricing theory. Not offered 2009–10.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6); second term.* A course on fundamentals of the mathematical modeling of stock prices and interest rates, the theory of option pricing, risk management, and optimal portfolio selection. Students will be introduced to the stochastic calculus of various continuous-time models, including diffusion models and models with jumps. Not offered 2009–10.

SS 216. Interdisciplinary Studies in Law and Social Policy. *9 units (3-0-6); second term.* A policy problem or problems involving the legal system will be studied, using concepts from at least one social science discipline. Each offering will be taught by a law professor, alone or in conjunction with a member of the social science faculty. The topic will differ from term to term, so the course may be taken more than once. Selected undergraduates may enroll in this course with the permission of the instructor. Instructor: Spitzer.

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 to understanding choice under risk and uncertainty, temporal discounting and self-control, advertisement and preference formation, addiction and other pathological behaviors, experienced utility, empathy, and trust. Instructors: Bossaerts, Camerer, Rangel.

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. Instructors: Sherman, Staff.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: SS 222 abc; may be repeated for credit.* A course in quantitative methods for second- and third-year social science graduate students. Instructors: Sherman, Matzkin.

SS 227. Identification Problems in the Social Sciences. *9 units (3-0-6); second term. Prerequisite: SS 222 abc.* There is a tension in modeling social science phenomena between making strong assumptions, which lead to descriptive or normative conclusions that are precise when the assumptions hold but invalid when they do not hold, and making weak assumptions, which lead to less precise conclusions but hold more generally. The preponderance of social science research to date takes the former approach. This course studies recent advances in the latter approach. The course will review the work of Manski on bounds identification and estimation and trace some of the developments in this line of research to the present. Various applications of the methodology will be considered, including applications to Stanford-9 test-score data and data on organic pollutants in the Love Canal. Not offered 2009–10.

SS 228. Applied Data Analysis for the Social Sciences. *9 units (3-0-6); third term.* The course covers issues of management and computation in the statistical analysis of large social science databases. Maximum likelihood and Bayesian estimation will be the focus. This includes a study of Markov Chain Monte Carlo (MCMC) methods. Substantive social science problems will be addressed by integrating programming, numerical optimization, and statistical methodology. Instructor: Katz.

SS 229 abc. Theoretical and Quantitative Dimensions of Historical Development. *9 units (3-0-6); first, second, third terms. May be repeated for credit.* Introduction to modern quantitative history. The tools of economic and political theory applied to problems of economic, social, and political development in a historical context. Second and third terms will be graded together. A pass/fail will be assigned in the second term and then changed to the appropriate letter grade at the end of the third term. Instructor: Rosenthal.

SS 231 abc. American Politics. *9 units (3-0-6); first, second, third terms.* A three-term course in American politics and political behavior. While drawing from contemporary materials, the course will emphasize the historical background of American political institutions. Instructor: Alvarez.

SS 232 abc. Historical and Comparative Perspectives in Political Analysis. *9 units (3-0-6); first, second, third terms.* Provides a knowledge and understanding of developments in both the American past and in other parts of the world. Instructor: Rosenthal.

SS 240. Techniques of Policy Research. *9 units (3-0-6). Prerequisite: SS 205 ab.* The application of social science theory and methods to the formulation and evaluation of public policy. Not offered 2009–10.

SS/CS 241 ab. Introduction to Social and Information Sciences. *9 units (3-0-6); second, third terms. Undergraduates cannot use this course towards fulfilling the core Institute social science requirement.* Introduction to techniques and methods used in research at the intersection of social and information sciences: aggregation of dispersed information and optimal allocation of resources through markets, networks, and other social systems; formation and off-equilibrium behavior of these systems; distributed cognition; related computational issues; aggregation, allocation, formation, and equilibration enhancements through technology—hardware and software, economic theory applied to the design of communication networks and computational systems; distributed information systems supporting economic activity. Instructors: EAS and HSS faculty.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (3-1-5).* For course description, see Computation and Neural Systems.

CNS/SS 252. Experimental Design and Research Methods in Cognitive Neuroscience. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6); third term. Prerequisite: SS/Psy/Bi/CNS 140 or instructor's permission.* This course will cover recent findings in the psychology and neurobiology of emotion and social behavior. What role does emotion play in other cognitive processes, such as memory, attention, and decision making? What are the component processes that guide social behavior? To what extent is the processing of social information domain-specific? Readings from the current literature will emphasize functional imaging, psychophysical, and lesion studies in humans. Instructor: Adolphs.

SS 260. Experimental Methods of Political Economy. *9 units (3-3-3).* 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 280. Modern Topics in Social Science. *9 units (3-0-6); first term.* This course will teach students about the major modern contributions of social science in fields outside their areas of specialization. Students will cover a series of basic topics by reading and discussing the central papers or books that characterize what is known about each topic area. Different sections of the course will be offered in different social sciences (e.g., economics and political science). Instructor: Camerer.

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. Instructor: Ledyard.

SS 283 abc. Graduate Proseminar in Social Science. *3 units (2-0-1); first, second, third terms.* Course for graduate students in social sciences. Students present their research and lead discussion of material relevant to their research program. Instructor: Rosenthal.

SS 300. Research in Social Science. *Units to be arranged.*

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Protection of Human Subjects [fills the role of Caltech's Institutional Review Board—IRB] (Reports to the Provost)—C. R. Plott, *Chair*; J. M. Allman (alternate), J. F. Baer (alternate), R. I. Feinberg, G. Fisher-Adams, A. Frey (adviser), G. Q. Jung, J. L. Kirschvink, P. Perona, C. Scislowicz*, R. P. Seligman*, J. M. Tyszka (adviser), H. M. Yohalem*, D. W. Zeh

Radiation Safety (Reports to the Vice President for Business and Finance)—D. S. Burnett, *Chair*; A. Asthagiri, B. Filippone, H. Issaian, W. L. Johnson, A. Kumagai, C. Scislowicz*

Sponsored Research (Reports to the Provost)—B. V. McKoy, *Chair*; T. H. Heaton, J. O. Ledyard, P. H. Patterson, N. C. Yeh

SURF (Reports to the Provost)—H. B. Gray, *Chair*; G. A. Blake*, D. Chan, J. O. Dabiri, S. C. Frautschi, K. M. Gilmartin, J. M. Jackson, G. Orton, W. M. Whitney, R. M. Wilson

**ex officio member*
†representing graduate students
‡representing undergraduate students
§representing postdoctoral scholars

FACULTY OFFICERS AND COMMITTEES 2008–09

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Chair: D. A. Dougherty
Vice Chair: S. M. Haile
Secretary: F. Cowie

Faculty Board

R. M. Alvarez, 2011
K. C. Border, 2012
M. E. Brown, 2010
D. C. Calegari, 2012
K. M. Chandy, 2010
J. O. Dabiri, 2010
S. E. Fraser, 2011
N. Lapusta, 2012
N. S. Lewis, 2010
V. J. Orphan, 2012
H. D. Politzer, 2012
W. Sargent, 2011
A. Stathopoulos, 2010
C. S. Steidel, 2010
D. J. Stevenson, 2011
B. Stoltz, 2012
Z.-G. Wang, 2011
E. Winfree, 2011

Ex Officio:
J. K. Barton
J.-L. Chameau
K. A. Farley
J. F. Hall
J. N. Katz
A. E. Lange
E. M. Meyerowitz
A. J. Rosakis
A. I. Sargent
J. E. Shepherd
E. M. Stolper

Steering

D. A. Dougherty, *Chair**
K. C. Border
F. Cowie*
D. G. Goodwin
S. M. Haile*
M. L. Hunt
S. L. Mayo
E. M. Stolper*

**ex officio member*

Academic Freedom and Tenure
J. Bercaw, 2010
S. Fraser, 2010
F. A. Harrison, 2010
J. A. Kornfield, 2011
P. Perona, 2011
J. H. Seinfeld, 2011

Academic Policies
P. M. Bellan, *Chair*
O. Aharonson, 2012
S. C. Frautschi, 2010
W. Goddard, 2012
J. E. Marsden, 2010
S. R. Quartz, 2012
J. D. Roberts, 2010

Athletics and Physical Education
M. R. Hoffmann, *Chair*
O. Aharonson, 2012
R. Bischoff*
R. H. Grubbs, 2012
L. Hillenbrand, 2010
W. J. Irwin*
J. L. Kirschvink, 2012
J. P. Wendell*
K. G. Zinn, 2012

Convocations
K. P. Giapis, *Chair*
S. M. Haile*
J. F. Hall*
C. Hitchcock, 2010
T. Schneider, 2010
J. E. Shepherd*
C. A. Weinstein, 2012

Core Curriculum Steering
B. W. Filippone, *Chair*
K. Gilmartin, 2012
M. B. Kennedy, 2010
N. S. Lewis, 2012
D. I. Meiron, 2010
E. Phinney III, 2011
J. Pine, 2011

Curriculum
F. Echenique, *Chair*
R. W. Clayton, 2010
J. F. Hall*
C. Hitchcock, 2010
M. N. Morley*
D. Rees, 2011
B. M. Simon, 2012
C. A. Weinstein, 2012

Educational Outreach
M. Feingold, *Chair*
M. Bronner-Fraser, 2010
S. Golwala, 2010
N. Lapusta, 2012

Exchange Programs and Study Abroad (CEPSA)
H. B. Newman, *Chair*
J. R. Goodstein (non-voting)
T. C. Ho, 2011
G. J. Laurent, 2011
M. N. Morley*
N. A. Pierce, 2010
W. Sargent, 2012
T. Schneider, 2012
D. J. Stevenson, 2010
L. Stolper*

Foreign Students and Scholars
A. G. Siapas, *Chair*
K. P. Giapis, 2010
M. Gooding*
Y. T. Hou, 2012
G. J. Laurent, 2011

Freshman Admissions
M. Aschbacher, 2010
J. L. Beauchamp, 2012
W. Bing (non-voting)
R. Bischoff*
N. R. Corngold, 2012
M. C. Cross, 2010
D. R. Kiewiet, 2012
B. McKoy, 2011
B. Megdal (non-voting)
O. J. Painter, 2012
S. Shimojo, 2010
D. Tsao, 2012
B. Wernicke, 2010

Graduate Studies
B. T. Fultz, *Chair**
R. W. Clayton, 2011
T. E. Colonius, 2011
S.-A. Hajimiri, 2011
J. E. Shepherd*

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Health
P. T. Hoffman, *Chair*
K. Austin*
D. M. Grether, 2012
W. Jack*
J. A. Kornfield, 2010
S. C. Miller*
P. H. Patterson, 2012

Institute Programs
J. Cohen, *Chair*
D. Bing*
J. R. Greer, 2012
K. Haugen, 2010
D. LaVertu*
S. Mazmanian, 2010
R. L. O'Rourke*
T. R. Palfrey, 2012

Library
J. H. Richards, *Chair*
C. E. Brennen, 2010
J. Bruck, 2012
R. A. Cameron, 2010
S. G. Djorgovski, 2012
K. Douglas*
R. C. Flagan, 2011
A. P. Ingersoll, 2012
J. M. Kousser, 2010
A. G. Siapas, 2012
C. Steidel, 2011
P. W. Sternberg, 2012

Membership and Bylaws
S. M. Haile, *Chair**
K. C. Border, 2010
F. Cowie*
M. Okumura, 2010
N. A. Pierce, 2010
T. Schneider, 2010
R. P. Sherman, 2010

Nominating
W. Sargent, *Chair*
K. M. Chandy, 2009
F. Cowie*
A. Stathopoulos, 2009
P. W. Sternberg, 2009
Z.-G. Wang, 2009

Patents and Relations with Industry
T. Colonius, *Chair*
F. H. Arnold, 2012
K. Bhattacharya, 2010
J. Bruck, 2011
M. Gharib, 2011
S.-A. Hajimiri, 2011
N. A. Pierce, 2011
A. G. Siapas, 2012
B. J. Wold, 2012
A. Yariv, 2011

Scholarships and Financial Aid
A. W. Blain, *Chair*
R. Bischoff*
G. Blake*
D. Crewell*
J. F. Hall*
J. L. Kirschvink, 2010
A. Kuppermann, 2012
G. Refael, 2012

Student Housing
J. Shepherd, *Chair*
T. Agapie, 2012
P. D. Asimow, 2011
G. A. Blake*
P. Daily (non-voting)
M. Iaryczower, 2011
W. Jack*
T. Mannion (non-voting)
B. J. McKeon, 2010
P. Wennberg, 2011
L. Yariv, 2011

Undergraduate Academic Standards and Honors
R. P. Sherman, *Chair*
W. C. Brown, 2010
J. L. Campbell, 2012
G. R. Gavalas, 2012
D. Goodwin, 2011
J. F. Hall*
M. N. Morley*
E. S. Phinney, 2012
D. P. Weitekamp, 2012

Upperclass Admissions
R. Bischoff*
D. Calegari, 2010
K. L. Haugen, 2012

**ex officio member*

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Christof Koch, *Executive Officer for Neurobiology*

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George Beadle Professor of Biology
Charles J. Brokaw, Ph.D.
Biology
John J. Hopfield, Ph.D.
Roscoe G. Dickinson Professor of Chemistry and Biology
Ray D. Owen, Ph.D., Sc.D.h.c.
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

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Roy J. Britten, Ph.D.
Distinguished Carnegie Senior Research Associate in Biology, Emeritus
Anne Chomyn, Ph.D.
Ellen G. Strauss, Ph.D.

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Bren Professor of Psychology and Neuroscience and Professor of Biology
John M. Allman, Ph.D.
Frank P. Hixon Professor of Neurobiology
Richard A. Andersen, Ph.D.
James G. Boswell Professor of Neuroscience
David J. Anderson, Ph.D.[1]
Seymour Benzer Professor of Biology
David Baltimore, Ph.D., D.Sc.h.c., D.Phil.h.c., Nobel Laureate
Robert Andrews Millikan Professor of Biology
Pamela Bjorkman, Ph.D.[1]
Max Delbrück Professor of Biology
Marianne Bronner-Fraser, Ph.D.
Albert Billings Ruddock Professor of Biology
Judith L. Campbell, Ph.D.
Chemistry and Biology
Eric H. Davidson, Ph.D.
Norman Chandler Professor of Cell Biology
Raymond Deshaies, Ph.D.[1]
Biology
Michael H. Dickinson, Ph.D.
Esther M. and Abe M. Zarem Professor of Bioengineering
William G. Dunphy, Ph.D.
Biology
Scott E. Fraser, Ph.D.
Anna L. Rosen Professor of Biology and Professor of Bioengineering
Bruce A. Hay, Ph.D.
Biology
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Christof Koch, Ph.D.
Lois and Victor Troendle Professor of Cognitive and Behavioral Biology and Professor of Computation and Neural Systems
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Bing Professor of Behavioral Biology
Gilles J. Laurent, Ph.D., D.V.M.
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Biology
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Thomas Hunt Morgan Professor of Biology
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Howard and Gwen Laurie Smits Professor of Cell Biology
Barbara J. Wold, Ph.D.
Bren Professor of Molecular Biology
Kai Zinn, Ph.D.
Biology

[1] *Joint appointment with Howard Hughes Medical Institute*

Associate Professors

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Biology
Michael Elowitz, Ph.D.[1]
Biology and Applied Physics
Bren Scholar
Grant J. Jensen, Ph.D.[1]
Biology
Athanassios G. Siapas, Ph.D.
Computation and Neural Systems
Bren Scholar

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Biology
Sarkis Mazmanian, Ph.D.
Biology
David Prober, Ph.D.
Biology
Angelike Stathopoulos, Ph.D.
Biology
Doris Ying Tsao, Ph.D.
Biology

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Carol Chace Tydell, D.V.M.

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Akiko Kumagai, Ph.D.

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Mary An-yuan Yui, Ph.D.

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Bruce Cohen, Ph.D.
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Jie Zhou, Ph.D.

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Ryan Michael Drenan, Ph.D.
Isabelle S. Peter Lashgari Faghani, Ph.D.
Constantin Georgescu, Ph.D.

Postdoctoral Scholars

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Meghan Adams, Ph.D.
Mark Aizenberg, Ph.D.[1]
Omar Akbari, Ph.D.
Bader Al-Anzi, Ph.D.
Roee Amit, Ph.D.
Constantinos Anastassiou, Ph.D.
Todd Anthony, Ph.D.
Kenta Asahina, Ph.D.
Young-Kyung Bae, Ph.D.
Alejandro Balazs, Ph.D.
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Julius Barsi, Ph.D.
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Smadar Ben-Tabou de-Leon, Ph.D.
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Catherine Bregere, Ph.D.
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Ariane Briegel, Ph.D.[1]
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Long Cai, Ph.D.
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Luca Caneparo, Ph.D.
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Songye Chen, Ph.D.
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Tsui-Fen Chou, Ph.D.
Willem den Besten, Ph.D.[1]
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EunJung Hwang, Ph.D.
William W. Ja, Ph.D.
Chathurani Jayasena, Ph.D.
Galina Jerdeva, Ph.D.
Yuling Jiao, Ph.D.
Snehalata Vijaykumar Kadam, Ph.D.
Mihoko Kato, Ph.D.[1]
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Jane Khudyakov, Ph.D.
Sally A. Kim, Ph.D.
Tamara Kinzer-Ursem, Ph.D.
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Hyosang Lee, Ph.D.
Hyung-Kook Lee, Ph.D.
Jinhwan Lee, Ph.D.
Enhu Li, Ph.D.
Long Li, Ph.D.
Wuxing Li, Ph.D.
Zhuo Li, Ph.D.[1]
Dayu Lin, Ph.D.[1]
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Irene Maier, Ph.D.
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Uri Maoz, Ph.D.
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Huu Ngo, Ph.D.
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Zachary Nimchuk, Ph.D.
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Periklis Pantazis, Ph.D.
Rigo Pantoja, Ph.D.
Rachel Penton, Ph.D.
Martin Pilhofer, Ph.D.[1]
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Nicolas D. Plachta, Ph.D.
Heidi Privett, Ph.D.
Konstantin Pyatkov, Ph.D.
Xiang Qu, Ph.D.
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Parameswaran Ramakrishnan, Ph.D.
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Hans Ingmar Riedel-Kruse, Ph.D.
Adrienne Roeder, Ph.D.
June Round, Ph.D.
Frederique Ruf, Ph.D.
Ueli Rutishauser, Ph.D.
Melissa Saenz, Ph.D.
Anjanabha Saha, Ph.D.
Amir Sapir, Ph.D.
Yuki Sato, Ph.D.
Ankur Saxena, Ph.D.
Erik Schlicht, Ph.D.
Celia Eenjing Shiau, Ph.D.
Alex Sigal, Ph.D.
Edward J. Silverman, Ph.D.
Marcos Wasada Simões-Costa, Ph.D.
Joel Smith, Ph.D.
Alex Yick-Lun So, Ph.D.
Alireza Soltani, Ph.D.
Cagdas D. Son, Ph.D.
Zhiyin Song, Ph.D.[1]
Amber Southwell, Ph.D.
David Sprinzak, Ph.D.
Jagan Srinivasan, Ph.D.[1]
Rahul Srinivasan, Ph.D.
Pablo Strobl Mazzulla, Ph.D.
Kaoru Sugimoto, Ph.D.
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Amere Swathi, Ph.D.
Paul Thomas Tarr, Ph.D.
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Anne M. Taylor, Ph.D.
Julia Tischler, Ph.D.
Elitza Tocheva, Ph.D.
Le A. Trinh, Ph.D.
Thai V. Truong, Ph.D.
Qiang Tu, Ph.D.
Cevat Ustun, Ph.D.
Jeroen van Boxtel, Ph.D.
Julien Vermot, Ph.D.
Marc Vermulst, Ph.D.
Sofia Vrontou, Ph.D.

Lorraine R. Washburn, Ph.D.
Kiichi Watanabe, M.D., Ph.D.
Casimir Wierzynski, Ph.D.
Claudia Beate Wilimzig, Ph.D.
Melanie Wilke, Ph.D.
Allan Wong, Ph.D.
Cheng Xiao, M.D., Ph.D.
Young Y. Yoon, Ph.D.[1]
Zhiheng Yu, Ph.D.
Alon Zaslaver, Ph.D.
Xiaolan Zhang, Ph.D.
Yan Zhang, M.D., Ph.D.
Lin Zhao, Ph.D.
Weiwei Zhong, Ph.D.[1]
Jelena Zinnanti, Ph.D.

[1] *Joint appointment with Howard Hughes Medical Institute*

Visitors

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Pranav Kosuri, B.S.
Mingzhi Liang, Ph.D.
Jasna Markovac, Ph.D.
Leonard Mlodinow, Ph.D.
Seth W. Ruffins, Ph.D.
Heiko Stemmann, Ph.D.
Andreas Walz, Ph.D.

Division of Chemistry and Chemical Engineering

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Richard C. Flagan, *Executive Officer for Chemical Engineering*
Mitchio Okumura, *Executive Officer for Chemistry*
Douglas C. Rees, *Executive Officer for Biochemistry and Molecular Biophysics*

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Elizabeth W. Gilloon Professor of Chemistry
John D. Baldeschwieler, Ph.D.
J. Stanley Johnson Professor and Professor of Chemistry
Sunney I. Chan, Ph.D.
George Grant Hoag Professor of Biophysical Chemistry
George R. Gavalas, Ph.D.
Chemical Engineering
John J. Hopfield, Ph.D.
Roscoe G. Dickinson Professor of Chemistry and Biology
John D. Roberts, Ph.D., Dr.rer.Nat.h.c., Sc.D.h.c., D.Sc.h.c.
Institute Professor of Chemistry
Nicholas W. Tschoegl, Ph.D.
Chemical Engineering

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Chemistry
William P. Schaefer, Ph.D.
Chemistry

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Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry
Jacqueline K. Barton, Ph.D., D.Sc.h.c., D.L.h.c.
Arthur and Marian Hanisch Memorial Professor and Professor

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Mary and Charles Ferkel Professor of Chemistry

John E. Bercaw, Ph.D.
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Geoffrey A. Blake, Ph.D.
Cosmochemistry and Planetary Sciences and Chemistry

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Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering

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Chemistry and Biology

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Warren and Katharine Schlinger Professor of Chemical Engineering

Peter B. Dervan, Ph.D., D.Sc.h.c.
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George Grant Hoag Professor of Chemistry

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Victor and Elizabeth Atkins Professor of Chemistry

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Materials Science and Chemical Engineering

James R. Heath, Ph.D.
Elizabeth W. Gilloon Professor and Professor of Chemistry

Julia A. Kornfield, Ph.D.
Chemical Engineering

Aron Kuppermann, Ph.D.
Chemical Physics

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
Arthur Amos Noyes Professor of Chemistry

Stephen L. Mayo, Ph.D.
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B. Vincent McKoy, Ph.D.
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Jonas C. Peters, Ph.D.
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Douglas C. Rees, Ph.D.[1]
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John H. Richards, Ph.D.
Organic Chemistry and Biochemistry

John H. Seinfeld, Ph.D., D.Sc.h.c.
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Brian M. Stoltz, Ph.D.
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David A. Tirrell, Ph.D., D.h.c.
Ross McCollum–William H. Corcoran Professor and Professor of Chemistry and Chemical Engineering

Zhen-Gang Wang, Ph.D.
Chemical Engineering

Daniel P. Weitekamp, Ph.D.
Chemical Physics

Ahmed H. Zewail, Ph.D., D.Sc.h.c., D.h.c., D.Univ.h.c., D.Phil.h.c., LL.D.h.c., M.D.h.c., Nobel Laureate
Linus Pauling Professor of Chemistry and Professor of Physics

[1] *Joint appointment with Howard Hughes Medical Institute*

Associate Professors

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Chemical Engineering

Linda C. Hsieh-Wilson, Ph.D.[1]
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Anand R. Asthagiri, Ph.D.
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Biochemistry
Thomas F. Miller III, Ph.D.
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Sarah E. Reisman, Ph.D.
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Sonjong Hwang, Ph.D.
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