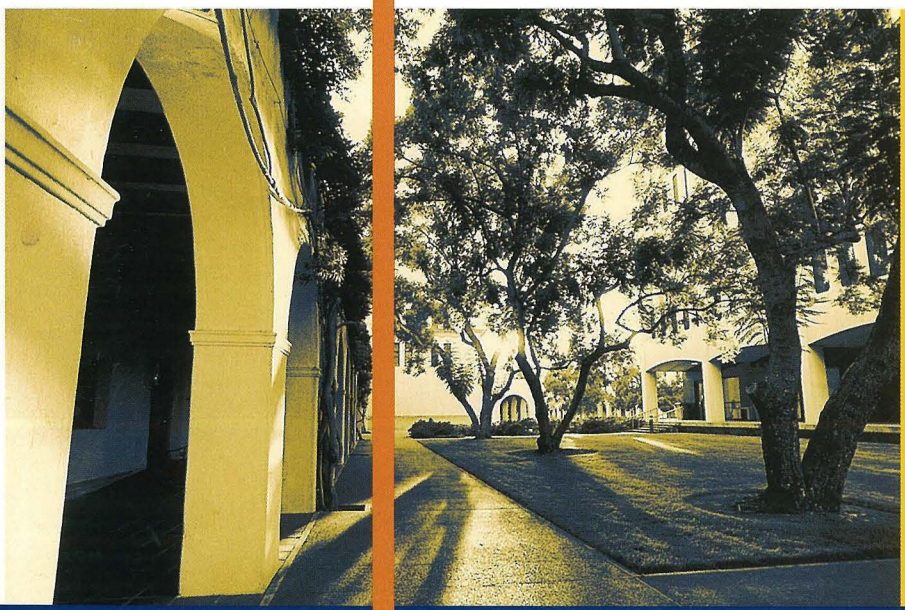
2000–2001

Caltech Catalog



2000–2001

Caltech Catalog

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

September 2000

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

The contents of the Web sites linked to course entries are not part of the official Caltech Catalog.

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ACADEMIC CALENDAR 2000–2001

FIRST TERM 2000

September 17
New-Student Registration for Undergraduates—Braun Gym, 10:00 a.m.–4:00 p.m.

September 18–20
New-Student Orientation for Undergraduates

September 19
New-Student Registration for Graduate Students—Braun Gym, 8:30 a.m.–noon
Orientation, 2:30–4:00 p.m.
Welcome and Information Fair, 4:00–7:00 p.m.

September 25
Beginning of instruction—8:00 a.m.
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

October 13
Last day for adding courses and removing conditions and incompletes

October 25–31
Midterm examination period

November 6
Midterm deficiency notices due—9:00 a.m.
Last day for admission to candidacy for the degrees of Master of Science and Engineer

November 13–24
Mail registration for second term, 2000–2001

November 15
Last day for dropping courses and changing sections

November 23–24
Thanksgiving holidays

November 23–26
Thanksgiving recess

December 1
Last day of classes
Last day to register for second term, 2000–2001, without a $50 late fee

December 2–5
Study period

December 6–8*
Final examinations, first term, 2000–2001

December 9
End of first term, 2000–2001

December 10–January 1
Winter recess

December 11
Instructors' final grade reports due—9:00 a.m.

December 22–26
Christmas holidays

January 1
New Year's holiday

SECOND TERM 2001

January 2
Beginning of instruction—8:00 a.m.
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

January 15
Martin Luther King Day holiday

January 23
Last day for adding courses and removing conditions and incompletes

February 2–8
Midterm examination period

February 12
Midterm deficiency notices due—9:00 a.m.

February 19
Presidents' Day holiday
Instructional Recess Day—classes do not meet

February 20–March 2
Mail registration for third term, 2000–2001

February 21
Last day for dropping courses and changing sections

March 9
Last day of classes
Last day to register for third term, 2000–2001, without a $50 late fee

March 10–13
Study period

March 12
Last day for obtaining admission to candidacy for the degree of Doctor of Philosophy

**First due date for final examinations*

March 14–16*
Final examinations, second term, 2000–2001

March 17
End of second term, 2000–2001

March 18–April 1
Spring recess

March 19
Instructors' final grade reports due—9:00 a.m.

THIRD TERM 2001

April 2
Beginning of instruction—8:00 a.m.
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

April 20
Last day for adding courses and removing conditions and incompletes

May 2–8
Midterm examination period

May 14
Midterm deficiency notices due—9:00 a.m.
Last day for seniors to remove conditions and incompletes

May 21–June 1
Mail registration for first term, 2001–2002, and registration for summer research

May 23
Last day for dropping courses and changing sections

May 25
Last day for presenting theses for the degrees of Doctor of Philosophy and Engineer

May 28
Memorial Day holiday

June 1
Last day of classes—seniors and graduate students

June 2–5
Study period for seniors and graduate students

June 6–8*
Final examinations for seniors and graduate students, third term, 2000–2001

June 8
Last day of classes—undergraduates
Last day to register for first term, 2001–2002, without a $50 late fee

June 9–12
Study period for undergraduates

June 11
Instructors' final grade reports due for seniors and graduate students—9:00 a.m.

June 13
Undergraduate Academic Standards and Honors Committee—9:00 a.m. (Commencement Meeting)
Curriculum Committee—10:00 a.m.
Faculty meeting—2:00 p.m.

June 13–15*
Final examinations for undergraduates, third term, 2000–2001

June 15
Commencement—10:00 a.m.

June 16
End of third term, 2000–2001

June 18
Instructors' final grade reports for undergraduates due—9:00 a.m.

June 27
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

July 4
Independence Day holiday

September 3
Labor Day holiday

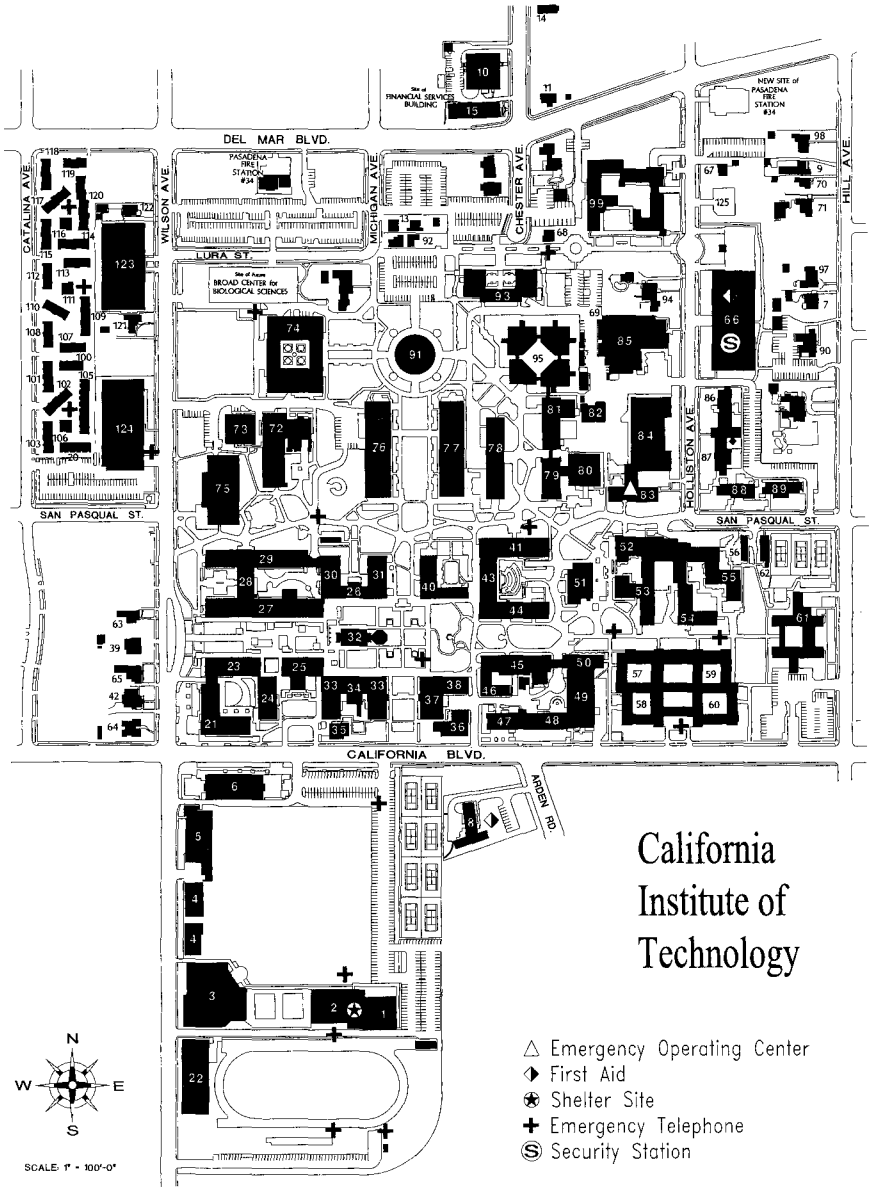
FIRST TERM 2001–2002

September 24–28
New-Student Registration and Orientation for Undergraduate students—Location and Time: TBA

September 25
New-Student Registration for Graduates—Location and Time: TBA
New-Student Orientation for Graduates, 2:30–4:00 p.m.
Welcome and Information Fair, 4:00–7:00 p.m.

October 1
Beginning of instruction—8:00 a.m.
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

**First due date for final examinations*



California Institute of Technology

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✱ Shelter Site
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Ⓢ Security Station

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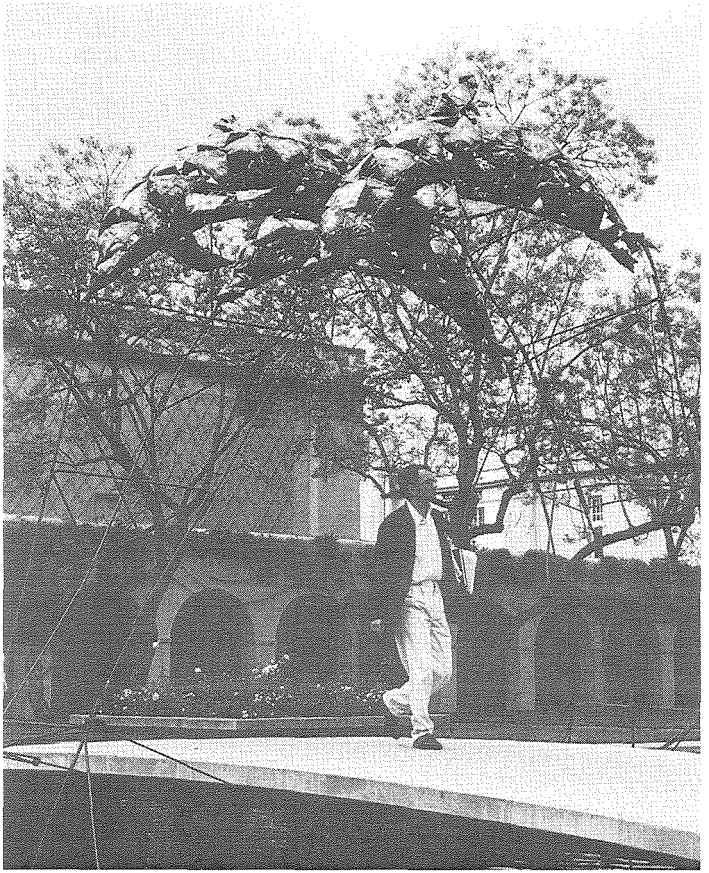
General Information



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 1,100 graduate students) and the members of a relatively large faculty (approximately 280 professorial faculty, 130 research faculty, and 400 postdoctoral scholars). "Caltech has achieved international influence far disproportionate to its size," according to *Time* magazine.

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, 985 Atlantic Ave., Ste. 100, Alameda, CA 94501; (510) 748-9001.

Undergraduate Program

Caltech offers a four-year undergraduate course with options available in applied and computational mathematics; applied physics; astronomy; biology; chemical engineering; chemistry; economics; electrical and computer engineering; electrical engineering; engineering and applied science; geochemistry; geology; geophysics; history; independent studies; literature; mathematics; physics; planetary science; science, ethics, and society; and social 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 55 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 aeronautics, applied and computational mathematics, applied mechanics, applied physics, astronomy, biochemistry and molecular biophysics, biology, chemical engineering, chemistry, civil engineering, computation and neural systems, computer science, control and dynamical systems, electrical engineering, engineering science/bioengineering, environmental engineering science, 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. They must have an earned doctorate from a duly accredited institution in virtually all circumstances. Upon arrival at the Institute, postdoctoral scholars should check in immediately at the Faculty and Postdoctoral Scholars Office in Parsons-Gates.

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. In 1921, when Dr. Norman Bridge agreed to provide a research laboratory in physics, Dr. 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 1,000 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 Aeronautical 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 in the science and technology of robotic space exploration. The Laboratory launched the U.S. space age in 1958 when it built Explorer I, the first American satellite. Four decades later, JPL is sending out a new generation of space explorers for NASA that build upon JPL's heritage of lunar and planetary missions such as Ranger, Mariner, Viking, and Voyager.

Missions have been launched or are being planned to Mars, comets, asteroids, the outer planets, and other targets of interest. New technologies are being proven in flight as JPL strives for faster, better, and cheaper spacecraft. The Stardust mission to intercept a comet and return a sample of comet dust to Earth has already collected interstellar dust for future return. Among other missions, Galileo to Jupiter has returned a wealth of new knowledge about the Jovian system, recently completing an extended mission and beginning yet another. Cassini to Saturn promises years of discoveries from the ringed planet. JPL also continues to manage NASA's worldwide Deep Space Network for spacecraft telecommunications, controlling spacecraft at the moon's distance and beyond.

JPL produced the Wide-Field Planetary 1 and 2 cameras for the Hubble Space Telescope, and brought astronomers a new view of the sky with the Infrared Astronomical Satellite (IRAS). The Space Infrared Telescope Facility, or SIRTF, is now being built for launch in 2001, and will be operated by the SIRTF team from the Caltech campus.

The Laboratory conducts a wide range of highly productive Earth observation experiments and missions studying the ocean, atmosphere, and land, including the U.S.-French TOPEX/Poseidon oceanographic satellite, the QuikScat/Seawinds mission to

measure near-surface wind speeds over the ocean surface, and the highly successful Shuttle Radar Topography Mission, which produced a high-resolution database of Earth's topography.

The Laboratory's program of research and development in space science and engineering has given rise to a dynamic commercialization and technology transfer program to move space program innovations into the private sector.

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 five years as wartime director of the MIT Radiation Laboratory—and remained 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 the $350 million Campaign for Caltech.

In October 1997, Dr. David Baltimore assumed the presidency of the Institute. Baltimore, one of the world's leading biologists, was the winner of the 1975 Nobel Prize for his work in virology. He was previously Ivan R. Cottrell Professor of Molecular Biology and Immunology at the Massachusetts Institute of Technology, and founding director of MIT's Whitehead Institute for Biomedical Research, serving from 1982 to 1990, when he became president of Rockefeller University. He had also earned his doctorate at Rockefeller in 1964. During the 1970s, he played a pivotal role with several other eminent biologists in creating a consensus on national science policy regarding recombinant DNA research, establishing research standards that are followed by the genetics community to this day. More recently, Baltimore has been a major figure in Washington as chairman of the National Institutes of Health AIDS Vaccine Research Committee. In 1999, he was awarded the National Medal of Science by President Clinton.

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

Caltech has more than 19,000 living alumni all over the world, many of them eminent in their fields of engineering and science.

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 (president)	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

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

* *In residence*

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.

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 substantial addition was built in 1947.

Athenaeum, 1930. A clubhouse for the teaching, research, and administrative staffs of the Institute and the Huntington Library and Art Gallery, 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, 1933–1943.

Undergraduate Houses, 1931:

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, 1917–1933.

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, 1907–1937, and of the Executive Council of the Institute.

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, 1924–1945.

Alumni Swimming Pool, 1954. Provided by the Alumni Fund through contributions of 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, 1926–1956.

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

Gordon A. Alles Laboratory for Molecular Biology, 1960. Erected with the gift of Dr. Gordon A. Alles of Pasadena, research associate in biology at the Institute, an alumnus, and a member of the Caltech Associates, 1947–1963; and with funds provided by the Health Research Facilities Branch of the National Institutes of Health.

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, 1939–1952.

Page House. Named in honor of Mr. James R. Page of Los Angeles, a member of the Board of Trustees, 1931–1962, and chair, 1943–1954.

Ruddock House. Named in honor of Mr. Albert B. Ruddock of Santa Barbara, a member of the Board of Trustees, 1938–1971, and chair, 1954–1961.

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.

Keck House. The gift of Mr. William M. Keck, Jr., of Los Angeles, who was a trustee from 1961 to 1982.

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

Mosher-Jorgensen House. The gift of Mr. Samuel B. Mosher and Mr. Earle M. Jorgensen, both of Los Angeles. Mr. Jorgensen was a member of the Board of Trustees, 1957–1999.

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, 1929–1949.

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, 1939–1968. Winnett houses the bookstore and the Red Door Café.

Beckman Auditorium, 1964. The gift of Dr. and Mrs. Arnold O. Beckman. Dr. Beckman, an alumnus, was a member of the Institute's faculty from 1928 to 1939. He has been a member of the Board of Trustees since 1953, was chair of the Board from 1964 to 1974, and is now chair emeritus.

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, 1921–1945.

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, 1919–1936.

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, 1930–1968.

Keith Spalding Building of Business Services, 1969. Named in honor of Mr. Keith Spalding, Caltech trustee, 1942–1961.

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 from 1957 to 1999.

The Mabel and Arnold Beckman Laboratories of Behavioral Biology, 1974. The gift of Dr. and Mrs. Arnold O. Beckman of Corona del Mar. Dr. Beckman is chair 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 from 1961 to 1992.

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, in recognition of their generosity to the Institute.

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

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

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

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 chair of the Board of Trustees.

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

Off-Campus Facilities

Kresge Building, Seismological Laboratory (Division of Geological and Planetary Sciences), 1928, 220 North San Rafael Avenue, Pasadena. Named in recognition of a gift from the Kresge Foundation of Troy, Michigan.

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, built by the Institute with funds from the Rockefeller Foundation.

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. Built with funds provided by Mr. and Mrs. William Gimbel, members of the Associates.

Beckman Institute

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

Center for Advanced Computing Research

In 1995, the Center for Advanced Computing Research (CACR) was established to ensure that Caltech and its Jet Propulsion Laboratory will be at the forefront in computational science and engineering (CS&E). CS&E is the practice of computer-based modeling for the study of scientific phenomena and engineering designs and typically involves a multidisciplinary investigation of interactions between the application, solution algorithms, computer architecture, and system software.

Computer-based modeling and simulation are indispensable for gaining a better understanding of many scientific phenomena and engineering designs. Computer simulation makes 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. In the realm of science, computer simulations are guided by theory as well as experimental results, while the computational results often suggest new experiments and theoretical models. In engineering, many more design options can be explored through computer models than by building physical ones, usually at a small fraction of the cost and elapsed time.

The CACR's mission is to foster advances in CS&E by

- following an applications-driven approach to computational science and engineering research,
- conducting multidisciplinary research on leading-edge computing facilities,
- providing a rich, creative intellectual environment that cultivates multidisciplinary collaborations, and
- harnessing new technologies to create innovative large-scale computing environments.

The CACR simultaneously provides leading-edge capabilities for CS&E research and experiments with new technologies that help define the technical computing environment of the future. Currently the CACR computing environment features a Hewlett-Packard 128-processor ccNUMA shared memory V-Class system, with 128 gigabytes of main memory and 1.15 terabytes of disk storage.

Industrial Relations Center

The Industrial Relations Center develops and offers programs on linking emerging technologies with management strategies and practices, 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's management library assists corporate clients and members of the Caltech community in locating information on managing technology, starting new business ventures, and developing the managerial skills of technical professionals.

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

Information Technology Services

Information Technology Services (ITS) provides technology infrastructure and support to Caltech and fosters the use of advancements and innovations in computing and networking technologies. ITS is a service organization with a focus on applying technology to serve the needs of faculty, staff, and students.

ITS operates several campus facilities and services including:

- the Digital Media Center (326 Sherman Fairchild Library, x3420, dmc@caltech.edu), providing specialized tools and equipment for working with digital media and for producing multimedia products and presentations;
- the Network Operations Center (233 Steele, x4602, network@caltech.edu), responsible for monitoring and managing the campus data network 24 hours per day;
- the Campus Computing Lab (214 Steele), open 24 hours per day, 7 days per week, and containing a variety of computers, including Macintosh, Windows NT, and Sun Solaris;
- a computer lab in each undergraduate house;
- a central computing Help Desk (x4602, help@caltech.edu) with dispatching services;
- system administration service serving academic departments;
- administration of campus site-wide software license agreements; and
- a computer repair facility.

The campus data network infrastructure, CITnet 2000, is installed, operated, and maintained by ITS in all buildings throughout campus. All student rooms in the undergraduate houses have full network access. ITS manages Caltech's high-performance links to the Internet and Internet2, as well as remote access to the campus network (including dial-up, cable modem access, and Virtual Private Networking). ITS provides several network-

based services, including Web, e-mail, Usenet, Domain Name Service, file transfer (FTP), and IP address assignment. Students are provided space for personal Web pages. The ITS Web site (http://www.its.caltech.edu/) provides additional details about facilities, services, and licenses provided by ITS.

Libraries

The Caltech Library System provides library resources and forward-looking information services of the highest quality in a timely, cost-effective manner to support and facilitate the research and educational programs of the Institute. The library system comprises the main collection in the Millikan Memorial Library; the Sherman Fairchild Library of Engineering and Applied Science; departmental libraries for astrophysics and geology; and a management library in the Industrial Relations Center.

The main library in the Robert A. Millikan Memorial Library includes the collections for biology, chemistry, mathematics, physics, and the humanities and social sciences. Circulation and customer services are on the first floor; microfilm and governmental document collections are on the fifth floor; and photocopy services are in the basement. The Sherman Fairchild Library includes engineering (chemical, electrical, civil, mechanical, environmental, and aeronautical), computer science, applied and computational mathematics, and materials science. Circulation and reference services are on the first floor, books and technical reports are on the ground floor, bound journals are on the second floor; and a reading room for current journals and newspapers is on the third floor. The Sherman Fairchild Library and the main library in the Millikan Memorial Library are open weekdays during the school year from 8 a.m. to 1 a.m., and weekends from 9 a.m. until midnight.

Collectively, the libraries subscribe to over 3,000 print journals, and 500 electronic journals; they contain 550,000 volumes, and have extensive collections of technical reports, government documents, and maps. The library electronic catalog includes the records of books and journals held throughout the Caltech Library System as well as active links to full-text resources. Also available on-line are the recent citations to articles from over 2,000 journals in science and technology, the social sciences, and art history, as well as a variety of electronic reference sources. Other special services that are available through the Caltech libraries include computerized literature searches, document delivery, and interlibrary loans. The Caltech Library System Web site at http://library.caltech.edu/ is a virtual reference desk with over 1,000 active pages.

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 and awards granted by the members of the SURF administrative committee. 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 luncheon roundtable discussions with leaders in business, government, or academia. Students may also take part in communications workshops on technical writing, presenting an oral report, and preparing visual aids. 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 2000, SURF students were paid $4,000. Applications are available in January and are due in early March. 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 Committee (UASH) 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, Room 137, Beckman Institute, (626) 395-2885, sfp@its.caltech.edu. Visit the Student-Faculty Programs Web site at http://www.its.caltech.edu/~sfp/ for more information on SURF and other programs.

STUDENT LIFE

Undergraduate Student Houses

The seven undergraduate student houses are situated on both sides of the Olive Walk near the eastern 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 seven is a separate unit with its own dining room and lounge, providing accommodations for about 75 students.

Each house has its own elected officers, and has wide power to arrange its own social events and preserve its own traditions. The immediate supervision of the activities of each house is the responsibility of the house Resident Associate, generally a married graduate student or younger faculty member. All houses are under the general supervision and control of the director of residence life.

In addition to the student houses, the Institute maintains two apartment buildings, two dormitories, 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 walking distance of the campus and offer students greater privacy, a different life style, and the opportunity to express their culinary creativity.

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 rooms for about 100 undergraduates and 25 graduate students, in addition to four faculty apartments and a visitor's apartment. 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 a regular series of lectures, performances, and social events open to the campus, and the house invites distinguished visitors to be in residence for varying lengths of time.

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. Whether you are interested in music, art, publications, student government, gaming, photography, Ping-Pong, or simply finding a room for your group to meet in, the SAC will probably have what you need. The center also houses the South House Laundry Room, and has several study halls, a small library, a bike shop, an arcade, and a TV/VCR room—most are open 24 hours. The center also includes a coffeehouse. The SAC is open to all current members of the Caltech and JPL communities, though first priority is given to undergraduate and graduate students.

The SAC provides office space for the officers of the graduate and undergraduate student governments, working space for student publications, office and rehearsal space for musical activities, and space for many more student-oriented functions. It also offers an array of services to the community, including SAC and Winnett room reservations, and club mailbox distribution. The staff is also able to assist students who need help planning a program or coordinating a new club.

Interhouse Activities

The president of each undergraduate house represents that house on the Interhouse Committee (IHC). While the seven 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 freshman selection process by which the houses choose their 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 parties, usually involving two or three houses, which are held once or twice each term.

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, such as course ombudsmen.

Freshman Advisers
Each member of the freshman class is assigned a faculty adviser. The adviser takes an interest in 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, intercollegiate competition is carried out in seven men's sports and five 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. A full 33 percent of Caltech undergraduates participate in intercollegiate athletics, and over 80 percent participate in some form of organized athletic competition each year.

Outdoor athletic facilities include a football field, an all-weather running track, a soccer field, baseball and softball diamonds, eight tennis courts, and two 25-yard swimming pools. Indoor facilities include two full-size gymnasia for basketball, volleyball, badminton, and gymnastics; 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, ASCIT is involved in

many aspects of student life. ASCIT subsidizes the Friday-night ASCIT movies, a weekly presentation of late-vintage popular films. ASCIT also oversees publication of the student newspaper, a directory, the yearbook, a research opportunities handbook, a course review, and a literary magazine.

Besides overseeing the 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 from time to time, 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 week-long New Student Orientation activities, and Gradiators, a fun-filled summer day of unusual games. *The Tèchnique*, an information guide for graduate-student life off and on campus, is published yearly 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. The GSC 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.

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*; a yearbook; a literary magazine; a student handbook, which gives a survey of student activities and organizations and serves as a campus directory; an annual review of the quality of teaching in the various courses; and a handbook of available research opportunities. These publications are staffed entirely by students. Through them, ample opportunity is provided for any student who is interested in obtaining valuable experience not only in creative writing, photography, art work, and the journalistic fields of reporting and editing, but in the fields of advertising and business management as well.

Musical Activities

The Institute provides qualified directors and facilities for a wind ensemble, a jazz band, several choral music groups, a symphony orchestra (jointly with Occidental College), a number of small chamber ensembles, and a weekly interpretive music class. A series of chamber music concerts is given on Sundays in Dabney Lounge. There are other musical programs in Beckman and Ramo Auditoriums.

Student Societies and Clubs

There are at the Institute 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.

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 stu-

dents. 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 Y is located in the Keck Wing of the Center for Student Services, on South Holliston Avenue. Run by undergraduate and graduate students and supported by endowments and Caltech's friends, it builds bridges between science and just about everything else: culture, politics, social consciousness, recreation, ethics, humanism, business, and leadership activities.

Pluralistic and nonsectarian, the Caltech Y is open to everyone, and extends its hospitality to students, faculty, and staff, no strings attached. It makes interest-free loans, sets up low-cost trips and backpacking adventures, subsidizes theater and sports tickets, administers the annual $3,000 Studenski travel award, has a copy machine and a TV/VCR, provides free outdoor campus concerts, runs a used-textbook exchange and the lost and found, provides a meeting room for campus organizations, rents camping equipment, sponsors guest speakers of national fame and local significance, plans many social and recreational activities, supports campus and community services, and coordinates the annual Leadership Institute. The Y offers a friendly atmosphere and a free cup of coffee with no membership lists, no fees, and no catches.

Ombudsperson

The Ombudsperson provides informal assistance in resolving intra-campus conflicts, disputes, and grievances and promotes fair and equitable treatment within the Institute. Any member of the Caltech community (students, faculty, and staff) may receive confidential and independent assistance from the Ombuds Office.

Religious Life

In addition to several groups active on campus such as the Caltech Christian Fellowship, the Newman Club, 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 150 public events, ranging from the traditional Earnest C. Watson Caltech Lecture Series to dramatic, film, and concert attractions (featuring world-renowned artists), are presented at Caltech. Tickets, often with discounts available, are offered to Caltech students for all events in Beckman and Ramo Auditoriums. Under the auspices of the Office of Public Events are a ticket

agency (handling tickets for Caltech events) and the campus Audio-Visual Services Unit (where projectors, tape recorders, and video equipment may be obtained).

Bookstore
The Caltech Bookstore 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 complete stock of general interest and reference books, insignia merchandise, greeting cards, and sundries. These are in addition to textbooks, and school and office supplies. The store offers an ordering service for books and items that are not a part of its regular stock. Located within the store are the Red Door Café and Caltech Wired Computer Store. The Red Door Café provides various types of coffee drinks and juices, along with other food items. Caltech Wired provides computers (including hardware and supporting software and instructional material) 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 two years 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: (1) office consultation and treatment of most medical problems by physicians and nurse practitioners (physician visits by appointment only and at prescribed hours); (2) laboratory tests, X rays, and consultations as ordered by the medical staff; (3) routine medications, prescription drugs, and other supplies at cost; (4) dermatology and orthopedic clinic visits, which are available on a weekly and bimonthly basis and are by appointment only.

Staff and faculty are seen at the Health Center for on-the-job injuries only.

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 substance-abuse prevention program, psychiatric consultation, and referrals to other professionals in the community. Counseling sessions are confidential.

Student Health Insurance

In addition to services available at the Health Center, coverage under a comprehensive medical insurance plan is provided to all full-time students and, during the summer, to students registered for the previous term. This plan covers (with a small deductible) hospital and surgical costs, as well as costs of outpatient treatment for injury or illness. Benefits continue for 12 months, on and off campus, provided that students remain enrolled through the school year.

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 Health Center.

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. To secure payment from the insurance plan and substantiate a claim for services rendered away from the Institute, the student is required to retain bills for such services and present them with appropriate documentation when medical claims are made. The Health Center office staff may be called upon for advice on the preparation of claim forms.

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.

CDC On-line
The CDC now has a home page on the World Wide Web with 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. Through the ASPIRE program, 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.

While students planning to apply to graduate school and other professional programs do not have to plan so far ahead, the CDC provides many resources for these programs as well. Important to all students who will seek further education is the Letter of Recommendation service for application to graduate or professional school.

On-Campus Recruiting Program
Through the on-campus recruiting program, employment interviews are arranged with about 200 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 Day
Each year in 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. Career Day 2000 hosted 99 different companies.

Ph.D. Career Fair
In recognition of the need for a more focused career fair to deal with special considerations of researchers with doctoral degrees, the Ph.D. Career Fair was developed. The event complements our annual Career Day in February, which traditionally has focused on undergraduates.

Career Library
The library contains college, graduate, and professional school catalogs, scholarship information, company literature, employer directories, career literature, and audio-visual resources.

Work-Study and Employment Listings
Job listings are maintained in the Career Library and through Jobtrak (http://www.jobtrak.com) 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 Self-Help: Employment and Loans, under Financial Aid in Section Three.)

A Summer Position in Research or Engineering (ASPIRE)
Caltech offers students a variety of internship experiences. Our traditional ASPIRE (A Summer Position in Research or Engineering) program 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.

In mid-2000, Caltech joined a consortium of universities forming Internship Partners Online, which is affiliated with monster.com. Through this affiliation, Caltech students have over 10,000 internship opportunities for which they can compete. There are opportunities in the arts as well as in the sciences, business, nonprofits, and government. Opportunities are local, national, and international.

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 provdes 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 December 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. (See Employment Experience of Recent Graduates, below.)

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

CALTECH ALUMNI ASSOCIATION

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

- the Alumni College, a two-day lecture series focused on one discipline, with Caltech faculty as featured speakers;
- Seminar Day, a day of lectures, exhibits, and social events held on campus;
- class reunions;
- domestic and overseas travel/study programs;
- regional events around the country, some of which showcase Caltech faculty.

The Association also supports on campus student activities and organizations, sponsors programs that encourage contacts between alumni and students, and funds scholarships and undergraduate awards. Alumni volunteers play an important role for the Association by representing Caltech at college fairs nationwide, by maintaining contact with prospective students and their families, and by serving as mentors to current students. Benefits of membership in the Alumni Association include a subscription to *Engineering & Science* magazine and an opportunity to join the Caltech Employees Federal Credit Union.

INTERNATIONAL STUDENT PROGRAMS

The Office of International Student Programs (ISP) provides assistance to international students and their dependents in adjusting to academic and personal life at Caltech and in the United States. The office provides assistance with cross-cultural adjustment, personal, financial, legal, career, and health-related needs of international students, in cooperation with other Institute departments and offices, and, where appropriate, acts as liaison with foreign government representatives in the United States. The office develops programs and activities that encourage interaction between international and U.S. students and promotes American students' participation in travel and study opportunities outside of the United States.

All visa and immigration-related matters for international students and their dependents are processed through the ISP. The staff disseminates information on the rules and regulations pertaining to all student visas, and represents students and the Institute to government agencies that oversee immigration regulations. The office is able to assist students with employment authorizations, extensions of stay, bringing dependents to the United States, changes of status, and any other immigration-related matters.

The staff of International Student Programs work closely with the graduate and undergraduate deans to address academic and personal concerns of international students. International students with a legal or an Honor System grievance or concern may contact the director for assistance.

The ISP plans and promotes programs and activities that foster international and cross-cultural awareness on campus. In cooperation with various national and cultural organizations and student governance groups, the office holds events that celebrate cultures and peoples of the world. The staff are resources for individual students and groups planning multicultural events.

The New International Student Orientation Program each September provides a comprehensive introduction to academic and social life at Caltech and in the United States. All incoming international students participate in this week-long program. In addition, the office holds information seminars throughout the year to update international students on immigration regulations, professional development, American values and work culture, and other appropriate topics.

The ISP issues international student ID cards for those traveling abroad. The office offers extensive resources on travel and study opportunities around the world. The ISP also assists students who are traveling abroad with cross-cultural and adjustment information, obtaining State Department travel information, and securing visas.

For information on English-as-a-second-language courses for graduate students, please refer to the list in Section Five, the course listing of this catalog.

Further information about services, current programs, and U.S. immigration regulations pertaining to nonimmigrant students can be obtained through the ISP Web site at http://www.its.caltech.edu/~isp_home.html.

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. 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 ordi-

narily 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.

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 following table.

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

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.

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.

- Each term any student may select, subject to such requirements as may be imposed by the option, one elective course 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.

NOTICES, AGREEMENTS, AND POLICIES

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. 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.

In specific degree programs the Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology has accredited our B.S. programs in chemical engineering, in electrical engineering, and in engineering and applied science. 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 Graduate Studies Office.

Nondiscrimination and Equal Employment Opportunity

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, which will take all reasonable steps to eliminate it in its work and academic environment.

(See the related harassment policy for more details.)

Caltech is committed to equal employment opportunity for all persons without regard to sex, race, creed, color, religion, national origin, ancestry, age, marital status, pregnancy, sexual orientation, status as a disabled veteran, a veteran of the Vietnam era or other eligible veteran, and for otherwise qualified individuals with a disability.

Caltech is an 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, place, transfer, and promote based on the qualifications of the individual and administer these functions to ensure equal consideration and fair treatment of all. All other employment actions, such as work assignments, compensation, evaluations, training (including apprenticeships and tuition assistance), benefits, layoffs, and terminations are governed by this policy. Personnel actions will be reviewed to ensure adherence to this policy.

Dr. Steven E. Koonin has been designated as the Equal Employment Coordinator for the faculty, Pamela J. Robertson for staff employees, and Dr. Jean-Paul Revel for students. 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. Likewise, management is responsible for monitoring decisions regarding personnel actions to ensure that these decisions are based solely on the individual's merit, and legitimate, nondiscriminatory job requirements for the position in question, and the reasonableness of any necessary accommodations for persons with a disability. Managers' performance in connection with Caltech's affirmative action goals and objectives will be evaluated as is their performance on other Institute goals.

Anyone who witnesses or experiences conduct they believe to be in violation of this policy is urged to contact any of the above identified coordinators, the individuals identified in the related harrassment policy, 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 Caltech's 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 or her responsibilities to contribute to its success.

Americans with Disabilities Act (ADA)

Caltech is committed to full compliance with the Rehabilitation Act (Section 504) and the Americans with Disabilities Act (ADA). Caltech's policy also prohibits discrimination against individuals with a record of disabilities or regarded as having a disability. As part of the implementation of this law, Caltech has adopted a policy that assures continued reasonable accommodation will be provided for qualified individuals with disabilities, which includes learning disabilities. Caltech's policy prohibits unlawful discrimination on the basis of disability in its programs, services, activities, and employment. It is the responsibility of the Caltech administration and faculty to ensure the Institute's compliance with this policy.

For information and services for the accommodation of graduate students with disabilities, please contact Dr. Sharyn Slavin Miller, Assistant Vice President for Student Affairs, (626) 395-6321. For undergraduate student assistance, please contact Dr. Barbara Green, Associate Dean of Students, (626) 395-6351.

Sexual Assault Policy for Students

I. Basic Principles

Rape and other types of sexual assault, whether by a stranger or by an acquaintance, are violations of the law and the policy of the California Institute of Technology. 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 will not tolerate sexual assault, whether directed at males or females. The Institute will also provide assistance and support for survivors of such assault and will aid in the apprehension of assailants. To reduce the risk of sexual assault, the Institute provides education to increase awareness of this important issue. Some of the educational programs provided include training for peer counselors, including health advocates; yearly training for resident associates; yearly inservice workshops for Student Affairs staff; and annual self-defense classes.

Caltech views sexual assault, in any of its forms, as a very serious matter and is committed to responding promptly and thoroughly to investigate sexual assault charges leveled at a Caltech student by any other of its students.

A student who has been sexually assaulted by another student or any other member of the Caltech community is strongly encouraged to file a complaint with Caltech officials, as well as with any civil authorities the student deems appropriate. See section III of this document for details on filing a complaint with the police.

II. Procedures for Filing a Complaint on Campus

Students who wish to file a complaint against another student should do so as soon as possible after the assault, although complaints may be filed at any time. Undergraduates should contact the dean or associate dean of students. Graduate students should see the dean or assistant dean of graduate studies.

If administrative changes are needed to protect the rights of either party, the dean shall see that they are made. Extensions to any time limits listed herein can be made if required for fairness or practical necessity. Such extensions will be made in writing and sent to the parties involved.

A. Initial Meeting

When a student ("the complainant") files a complaint with one of the deans, the dean will:

- Ask the complainant questions to assess the situation for continuing threat to the complainant and/or other members of the community.
- Ensure that the complainant is given appropriate protection if necessary, including protection from retaliation for the complaint. Such protection may include a temporary housing reassignment and other restrictions on the accused ("the respondent").
- Request a written statement of complaint from the complainant that includes as much detail as possible.
- Provide a copy of these procedures to the complainant.

B. Investigation

Within a reasonable amount of time (typically five working days) of meeting with the respondent, the dean will form a two-person team to investigate the case. The dean may choose to be one of the members of that team. The Institute will try to protect confidentiality. The degree to which confidentiality can be protected, however, depends upon the professional role of the person being consulted. For example, doctors and nurses who treat injuries sustained during sexual assaults are required to report to law enforcement. The professional being consulted should make these limits clear before any disclosure is made to them.

In addition, campus security is required by law to report to police certain factual details about incidents occurring on campus. Such reports are for statistical purposes and do not include individual identities. State law permits law enforcement authorities to keep confidential the identity of a person officially reporting a sexual assault. However, if the District Attorney files a criminal charge, confidentiality may not be maintained. The investigation should be completed within 21 days after the formation of the team. The Caltech investigation will occur independently from any

legal proceedings that may take place. The 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.
- Both investigators will interview the complainant and will interview the respondent, and each will be allowed to have a friend, who is not a lawyer, 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.
- The complainant will be kept informed of the status of the investigation.

C. Determination

The investigators will consult with Institute counsel and, when the dean is not a member of the team, make a recommendation to the dean regarding the charges and the appropriate consequences, including discipline up to expulsion for the respondent.

In addition, the investigating team shall prepare a summary record of the case for the dean. This record will be considered a confidential Institute document and will be available only to the vice president for student affairs, the provost, and the president in case of an appeal.

D. Resolution

The dean may 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.

The dean 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 dean will carry out any disciplinary consequences if the respondent is a student. Discipline for students can include, but is not limited to, the following: verbal counseling, probation, involuntary leave, and expulsion. If the complainant is found to have acted in bad faith in bringing the charges, disciplinary action may also be taken.

E. Appeal

Either the complainant or the respondent may appeal the decision to the vice president for student affairs. The appeals must be on the grounds of improper procedure or an arbitrary decision based on evidence in the record. The vice president may interview both parties and consult with the investigators before deciding whether to accept the judgment of the dean or authorize further investigation or deliberations.

III. Filing a Complaint with Civil Authorities

If a student wishes to report a rape to the police, the student is encouraged to seek support and guidance from the Caltech Women's Center. They have experience in this area and can be very helpful. Their telephone number is (626) 395-3221. The telephone number for the Pasadena Police is (626) 405-4501.

Because sexual assault may involve physical trauma and is a crime, the survivor is encouraged to seek medical treatment at Huntington Memorial Hospital Emergency Room. This is necessary if the survivor wants evidence collected and is possible only if the assault occurred within the last 72 hours. The survivor also will be informed that because the assault is a crime, the hospital has an obligation to inform the police and that the police will conduct an interview at the hospital regarding the assault. The survivor can choose whether or not to disclose information to the police. The survivor's consent will be requested to allow collection of evidence and the survivor may choose to go forward with a criminal or civil prosecution.

To preserve evidence, the survivor should not shower, douche, or change clothes. The survivor should bring a fresh change of clothes to the hospital. If clothes have been changed, the clothes worn at the time of the assault should be put in a paper bag and brought to the hospital.

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

IV. Community Resources

Verbal and written information about sources of support on campus and in the community will be provided to the survivor. Referrals to the following will be included:

Student Health Center	395-6393
Caltech Counseling Service	395-8331
Caltech Women's Center	395-3221
Office of the Dean of Students	395-6351 or
Dean of Graduate Studies	395-6367
Office of Residence Life	395-6194
Planned Parenthood	798-0706
Victim/Witness Assistance Program	356-5714
Pasadena Lawyer Referral Services	795-5641

V. Further Complaints

The complainant should notify the dean immediately if anyone associated with this matter is under continuing threat. In such cases, the complainant has the right to file another complaint.

On a "need-to-know basis," the following individuals or offices 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. The names of the individuals involved will not be released without their consent unless the release is essential to the health and safety of a student or to otherwise fulfill the legal obligations of the Institute. In such rare circumstances, the vice president for student affairs is the only one 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 will be notified as soon as possible.

The President
Vice President for Student Affairs
Assistant Vice President for Student Affairs
Dean of Students/Dean of Graduate Studies
Director of Residence Life/Master of Student Houses
Resident Associate
Director of the Women's Center
Director of the Student Counseling Services
Director of the Health Center
The Office of Public Relations
Campus Security

Institute Policy on 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, sexual orientation, or any other characteristic protected by state or federal laws, is prohibited, as are all forms of sexual intimidation and exploitation.** All students, staff, and faculty should be aware that the Institute will not tolerate any conduct that constitutes illegal harassment. 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.

Faculty, staff, and students have the right at any time to raise the issue of harassment without fear of retaliation. Any faculty or staff member or student who feels that he or she has been harassed should review the Procedures for Investigating and Resolving Unlawful Harassment and Sexual 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.

Director, Employee Relations
Division Administrators
Division Chairs
Provost
Deans
Student Affairs Directors (including the Master of Student Houses)
Employee Relations Specialists

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:

Ombuds Office
Staff and Faculty Consultation Center
Counseling Center
Women's Center

Information for faculty, students, and staff is also available from the Women's Center, Ombuds Office, Staff and Faculty Consultation Center, any Student Affairs office, or the Resident Associates.

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 individuals. 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 of 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.

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, sex, and sexual orientation.

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, 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.

Of course, in order to make an accurate judgement 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 will therefore 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 such an 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 for "unwelcome" is not whether the participation was voluntary; the test is whether the conduct was unwelcome.

Peer or coworker sexual harassment 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; displaying sexually suggestive objects, pictures, cartoons, posters, calendars, or computer screens.
- Making or using derogatory comments, epithets, slurs, or jokes of a sexual nature.
- Verbal sexual advances or propositions.
- Creating or obtaining sexually explicit materials using Institute resources or time 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, 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. 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, dean, or division chair has the authority to eliminate 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 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.

Procedures for Investigating and Resolving Unlawful Harassment and Sexual Harassment Complaints at Caltech

I. Basic Principles

Caltech is dedicated to the free exchange of ideas and intellectual development as part of the campus milieu. 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.

The Institute is committed to maintaining a work and study environment for all members of the Caltech community that is free of unlawful harassment, including sexual harassment. Harassment compromises the tradition of intellectual freedom and the trust placed in the members of the Caltech community. This policy is not intended to stifle vigorous discussion and debate, teaching methods, or freedom of expression generally. Harassment, as defined in the Institute's policy on harassment, is neither legal nor the proper exercise of academic freedom. Retaliation against an individual for reporting any type of harassment is also prohibited by law and Caltech policy.

Copies of the Institute's discrimination and harassment policies are available from the Human Resources Office, any Student Affairs office, the Women's Center, the Ombuds office, the Staff and Faculty Consultation Center, and the Provost's Office, are published in the Caltech *Catalog*, and the employee handbook, and are on the Caltech Web site. The policy and these procedures identify appropriate people on campus to contact with complaints.

II. 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 the individual ("the complainant") to address the prob-

lem, each with different consequences and implications with respect to confidentiality and resultant action. These include the following five possibilities.

Steps 1–4:

In general, the goal of steps 1–4 is to put an end quickly to the offending behavior without utilizing disciplinary action. Third parties with an official status at Caltech as described in step 4 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.

1. Talk personally with the offending individual, or write a letter asking him/her to stop. This is a personal step taken solely among the relevant parties.
2. Speak to members of the Counseling Center, the Ombuds office, the Staff and Faculty Consultation Center, or the Women's Center. Such conversations are confidential and are not communicated to individuals within or outside the Institute.
3. Resolve 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 respon sibility at Caltech.
4. Resolve 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 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 shar ing some of this information with other persons holding positions of responsibility at Caltech.

Step 5: Formal Complaints

A formal complaint is a request that the Institute take action. Complainants 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 specialist, student affairs director (including master of student houses), division chair, division administrator. The complaint is

then taken to the provost, director of employee relations, or dean(s) as appropriate (for faculty or postdoctoral scholars, staff, and students, respectively). This individual initiates an investigation. Step 5 is described more fully below.

These options are not mutually exclusive. The complainant has the right to choose which course to follow and is urged to submit a formal complaint in the event that informal steps do not stop the behavior.

Protection of complainant: The Institute encourages staff, faculty, and students to report and address incidents of harassment. Accordingly, 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, 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, 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. Complainants 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.

Details of Formal Complaints

Formal complaints of harassment can be made orally but should, in the end, be submitted in writing. Complaints should be brought to the attention of one of the following individuals: provost, dean, director of employee relations, employee relations specialist, student affairs director, division chair, 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 reasonable length of time of the notification of the complaint, normally within 120 days. The investigation may be carried out by an individual, a committee, or an outside consultant. 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 on various aspects of harassment. Because of the sensitive nature of these investigations, she/he 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 Equal Employment Opportunity (EEO) and harassment policy and 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. 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.

All parties who participate in interviews may submit written statements. Investigatory meetings will not be recorded. Findings and conclusions in the case will be reported, along with recommendations regarding resolution and sanctions appropriate to the case, to the respondent's management/administration within 30 days of the investigation being concluded. The findings should also recommend measures that could prevent the occurrence of similar instances.

Exceptions to or modification of these procedures can be made by the provost, dean(s), or 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], or director of employee relations as needed.

Investigative files are confidential and will be maintained in the appropriate administrator's office.

Resolution

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 belief that a basis existed.

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

If a violation of the 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 she or he violated other Institute policy or committed some other wrongful or improper act, or if the complainant is found to have brought charges without any basis or without a reasonable belief that a basis existed, appropriate sanctions will be imposed.

Appeals

Appeals must be in writing and 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.

Staff appeals can be made to the assistant vice president for human resources.

Further Complaints

The complainant should notify the provost/division chair, 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.

Student Grievance Procedure

Caltech provides a variety of routes, most of them informal, by which student complaints are brought to consideration and resolution. In academic matters, for example, they may begin with teacher-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 director of residence life. The dean of graduate studies is often of assistance in resolving graduate student matters. As the Institute officer responsible for the supervision of many Student Affairs offices, the assistant vice president for student affairs may be the appropriate person to appeal to in case of unresolved complaints involving those offices. The ombudsperson, who acts on behalf of the entire Caltech community, may be consulted confidentially about any problem. 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 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, Director of Residence Life, Women's Center, and the Ombuds Office.

Employment Experience of Recent Graduates

A survey was made at the end of June 1999 of the future plans of students who had graduated earlier that month.

Of those receiving the B.S. degree about whom Caltech has definite information, 42 percent had been accepted for admission to graduate or professional school for further education, 27 percent had accepted employment, 17 percent were uncommitted, and 9 percent had other plans. The average salary of those accepting employment was $55,126 per year. At the M.S. level, 71 percent had continued in graduate school, 12 percent had accepted employment at an average salary of $53,000 per year, 4 percent were uncommitted, and 9 percent had other plans. Of those receiving the Ph.D. degree, 1 percent had continued in graduate school, 33 percent had accepted industry employment with an average salary of $72,553 per year, 52 percent had accepted faculty or research fellow positions, 3 percent were uncommitted, and 5 percent had other plans.

Student Retention and Persistence Rates

Most undergraduates enter Caltech at the freshman level. Of the 254 freshmen enrolled during the 1998–99 academic year, 249 have reenrolled in the first term of the 1999–2000 academic year and are progressing, yielding a persistence rate of 98 percent. Of the 209 freshmen enrolled during the 1993–94 academic year, 171 graduated by June 1999, yielding a graduation rate for this group of 82 percent. At the graduate level, 91 percent of entering students graduate with the degree of either Master of Science or Doctor of Philosophy or, occasionally, both.

Student Patent and Computer Software Agreement

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 (including programs, databases, and associated documentation) to be written, and it is important that the student's rights in patents on inventions and in computer software he or she may have made or written be protected. The Institute's policy generally is to reserve to itself rights in inventions and computer software made 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 generally retain all rights except in inventions or computer software made 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 both of the student and of the Institute, each entering student is asked to sign the following agreement:

1. The Institute agrees that I shall retain all rights in inventions and computer software made or written by me except when such inventions are first conceived or reduced to practice or

such computer software written: 1.1 in the course of the performance of work as a paid employee of the Institute; 1.2 in the course of independent student research financed by or otherwise obligated to an outside grant or contract to the Institute or financed by a grant from the Institute; 1.3 or when they arise out of work in the research program of an academic staff member.

2. The Institute agrees that rights of all other inventions or computer software made or written by me with the use of Institute facilities are to be retained by me, except for computer software that is written in connection with or used in the educational program of the Institute (e.g., course work, homework, theses), for which 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 first written, under the conditions of items 1.1 or 1.2 or 1.3 above and computer software written in connection with or used in the educational program of the Institute under the conditions of paragraph 2 above.
4. I agree to assign to the Institute or its nominee all rights in the United States and foreign countries to inventions and computer software made or written under the conditions of items 1.1 or 1.2 or 1.3 above and to supply all information and execute all papers necessary for the purpose of prosecuting all patent applications, or registering copyrights in or otherwise protecting such computer software, and fulfilling obligations that may arise from such inventions or computer software. The Institute will bear the expenses for such patent applications or copyright registrations or for obtaining such other protection.

It is understood that the student will share in the same manner as a member of the academic staff such royalty income from patents or computer software as the Institute may receive on inventions assigned to it, or computer software assigned or licensed to it, as a result of this agreement.

It is also understood that the Institute relies on the foregoing agreement when it signs contracts with others and obligates itself with respect to discoveries, innovations, or inventions or computer software made or written in the course of research conducted at the Institute under such contracts.

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 Women's Center staff), a person with whom the Institute has contracted (such as an attorney, auditor, or collection agent), or a person serving on the Board of Trustees. A school official has a legitimate educational interest if the official 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 academic and business purposes of the Institute. Records involving financial aid are maintained by the director of financial aid, and are available to the director and staff, to the dean of graduate studies and staff, to the Faculty Committee on Scholarships and Financial Aid, and to the Faculty Committee on Graduate Study, for the purpose of granting and administering the Institute's Financial Aid program. Except as authorized by federal or state law or regulation, none of these educational records nor any personally identifiable information contained therein, other than directory information (see below), will be made available to anyone else, other than the student, without the written consent of that student. Where consent is required and given, the student, upon request, will receive a copy of the records to be released. The Institute will keep a record, available to the student and kept with his or her file, of all persons and organizations, other than those authorized within the Institute, requesting or obtaining access to the files, except when records have been produced in response to a grand-jury subpoena or other subpoena issued for a law-enforcement purpose and the court or issuing agency has ordered that the existence or the contents of the subpoena or the information furnished in response to the

subpoena not be disclosed.

2. Students are allowed access to their educational records as follows: A student may inspect his or her academic transcript during normal working hours. To see other records, the student must provide a written request to the registrar or to the director of financial aid or to the dean of graduate studies or to the dean of 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, gender, address, e-mail address, telephone listing, date and place of birth, major field of study, year in school, 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 is made generally available to requestors. 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, records, access to which has been requested, are not allowed to be and will not be destroyed until such access has been granted, or denied as described in (2) of this section.
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 Ave. SW, Washington D.C. 20202-4605.

Academic Records of Veterans

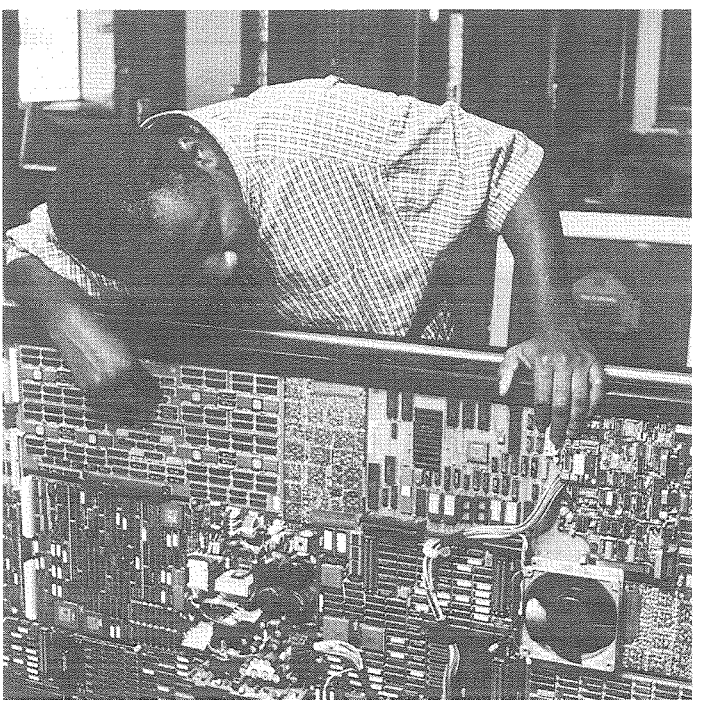
The Institute maintains a written record of a student's previous education. This is part of the student's permanent record card, and included on this is a summary of any prior college-level education. A true copy of a transcript of college-level work at other institutions is maintained as part of the student's record. The amount of credit granted for prior training is indicated on the student's permanent record card 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 permanent record card 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 permanent record card.

Study and Research



AERONAUTICS

The Guggenheim Aeronautical Laboratory, the Karman Laboratory of Fluid Mechanics and Jet Propulsion, and the Firestone Flight Sciences Laboratory form the Graduate Aeronautical Laboratories, widely known as GALCIT. In this complex are housed the Applied and Computational Mathematics group, the Jet Propulsion Center, and the Hydrodynamics Laboratories, as well as the various disciplines making up the broad field known as aeronautics.

Areas of Research

Aeronautics 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 structural mechanics. Research at GALCIT has traditionally pioneered exploration of new areas that have anticipated subsequent technological demands. Thus, for example, research in transonic, supersonic, and hypersonic fluid mechanics began before the advent of supersonic flight and the development of vehicles for reentering the earth's atmosphere. Research in plasma dynamics began before the importance of controlled fusion was recognized; in turbulent mixing, before the appearance of the chemical laser, the need for optimizing combustion, and the drive to reduce jet noise. Similarly, research on problems of shell structures began before their widespread use in aircraft, and undoubtedly stimulated this development. Work in fracture mechanics of polymers was initiated before composite materials became an important component of aerospace structures. This tradition places a high premium on an in-depth understanding of fields both closely and remotely related to the behavior of fluids and structures, such as physics, applied and computational mathematics, geophysics, materials science, electronics, and even astrophysics. As a consequence, 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 study and research currently pursued by aeronautics 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 gasdynamics, diffraction of shock waves, detonation waves, shock-induced Rayleigh-Taylor instability, and transient supersonic jets; the development of laser scattering diagnostic techniques for fluid-flow measurements; and studies of two-phase flows, vapor explosions, dusty gases in transient flows, and explosive volca-

noes. Students in applied physics are also able to pursue various problems in the physics of fluids under the supervision of members of the aeronautics faculty.

- *Computational Fluid Dynamics.* In computational fluid dynamics, fluid flows are investigated by computer simulation. Present active research areas include the study of structures and mechanisms in transition and turbulence, the study of flows with large-scale separation, the study of hypervelocity flows, and the design of new algorithms. Computers and computing techniques have improved to the point that they are a valuable complement to laboratory investigation.
- *Technical Fluid Mechanics.* Research at GALCIT includes a long history of work on subsonic and supersonic turbulent boundary layers, shear flows, and separated flows. These areas are related to a variety of modern technological problems and, in addition, to the traditional aeronautical problems of drag, wing stall, and jet mixing. Additional areas of activity include bluff-body aerodynamics, turbulent combustion, laminar diffusion flames and their instabilities, fires in buildings (turbulent mixing and flow fields driven by fire-produced buoyancy), explosions, hydrodynamics and two-phase flows, interaction of vorticity with free-surface, cardiac flows, and active and passive control of transition and turbulence.
- *Structural Mechanics.* Structural mechanics research involves both the static and dynamic behavior of structures and solids. Included are buckling for both elastic and viscoelastic (composite) materials. Other subjects include the response and failure of composite materials, including high-temperature ceramics and composites that find application in future high-speed flight.
- *Computational Solid Mechanics.* As a field of endeavor, computational solid mechanics addresses phenomena ranging from the atomistic scale, e.g., nanoindentation, to the structural scale, e.g., fracture of aircraft components. 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, automobiles, and bridges. The goals and objectives of the computational solid mechanics facility at Caltech 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 medium-scale simulations in solid mechanics; and to serve as an instructional facility for advanced courses in computational solid mechanics.
- *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 fracture studies in polymers are the nonlinearly viscoelastic behavior of polymeric solids, and issues of durability in advanced aerospace structures.

- *Aeronautical Engineering and Propulsion.* Research work in the field of aeronautics 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 gas turbine components (principally axial flow compressors and combustion chambers), rocket engine combustion chambers, and ramjet engines.
- *Aero-Acoustics.* A number of topics in the broad field of aeroacoustics are actively under study at GALCIT. They include jet noise, combustion noise, and nonlinear acoustics and hydroacoustics. A particularly interesting problem is the generation of combustion-induced organ pipe oscillations in large burners of electric generating plants.
- *Jet Propulsion.* The Daniel and Florence Guggenheim Jet Propulsion Center conducts a large portion of its instruction and research in close cooperation with the aeronautics group. Students wishing to pursue courses of study and research in jet propulsion take degrees in aeronautics or mechanical engineering. The program generally emphasizes basic subjects (such as combustion, two-phase flow, turbomachinery, fire research, acoustics) that are applicable to a wide variety of engineering problems. The experimental facilities of the Jet Propulsion Center are located in the Karman Laboratory of Fluid Mechanics and Jet Propulsion. Some of the facilities of the Jet Propulsion Laboratory have also been used under special arrangement.

Physical Facilities

The Graduate Aeronautical Laboratories contain a diversity of experimental facilities in support of the above programs. Low-speed wind tunnels include 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. A smaller water channel for studies of wave motion and flow visualization is also available. For investigations of high-speed flows there is a supersonic wind tunnel with two different working sections and a shock tunnel for studying hypervelocity gas flows up to 7 km/s. Shock tubes, plasma tunnels, and other special facilities are available for the study of extreme temperatures, shock waves, deflagrations, detonations, acoustics, and cryogenic flows.

The solid mechanics laboratories contain standard as well as special testing facilities for research related to aircraft, spacecraft structures, and failure/fracture behavior of materials under static and dynamic loads, including three servohydraulic facilities, two of which operate on a "tension/torsion" mode. Fatigue machines and photoelastic equipment are available, as well as special apparatus, including laser equipment and a line of high-speed cameras offering recording at rates from still to 2 million frames per second, for the study of fast phenomena, e.g., wave propagation, dynamic buckling, 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 temperature measurements, both for static and dynamic applications.

State-of-the-art electronic instrumentation is being developed and used. Computer systems for real-time control of experiments, for data acquisition, processing, and storage, and for digital image processing are used extensively.

Computational facilities range from personal computers and powerful workstations to an on-campus large-scale parallel processing machine, and remote supercomputers such as those generally available at NSF and NASA centers. Graphics workstations are available to support research in computational fluid dynamics and computational solid dynamics. These workstations provide high resolution color graphics, with the capability of viewing three-dimensional information at high speed, a large storage capability, and a network interface so that programs and results can be sent to and from remote supercomputers.

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. Close contact is maintained with experimental programs in fluid and solid mechanics and with research groups in parallel computation. The applied and computational

mathematics group has access to supercomputers and concurrent computers, and has a variety of its own computers, graphics terminals, and other equipment. 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, stochastic processes, mathematical programming, numerical analysis, 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 present group primarily interested in applied and computational mathematics 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, 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, mathematical programming, stochastic processes, 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 vibrations; structural dynamics and control for earthquake and wind loads; linear and nonlinear prob-

lems in static and dynamic elasticity, plasticity, and viscoelasticity; wave propagation in solids; 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 matter in bulk 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 activities cover a broad spectrum, ranging from cryogenics to plasmas, from rarefied gas flow to high pressures and shock waves in solids, from particle transport to planetary science. There is research in progress in the physics of solids, including solid-state electronics, amorphous solids, quantum electronics, and superconductivity; in the physics of fluids, including plasmas and magnetohydrodynamics, liquids, and superfluids; and in the physics of electromagnetic radiation, including linear and nonlinear laser optics and electromagnetic theory. The research program is enriched by the 40,000-square-foot Thomas J. Watson, Sr., Laboratories of Applied Physics. This attractive building contains offices around a central courtyard and laboratories on the balance of the two floors. Conference rooms and a large classroom occupy the single-story entrance wing.

ASTRONOMY

The astronomical observatories at Palomar and Mauna Kea, and the Owens Valley Radio 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 newly established SIRTF Science Center (SSC). For example, IPAC currently supports a number of NASA missions: 2MASS,

an all-sky survey at 2 microns, and Infrared Space Observatory (a mission of the European Space Agency). The SSC will conduct the science operations of the Space Infrared Telescope Facility—one of the great space observatories.

The Division of Physics, Mathematics and Astronomy also conducts work in theoretical astrophysics, laboratory astrophysics, gravitational-wave physics, and infrared and submillimeter astronomy. The radio astronomy group works in close collaboration with the optical astronomers in Pasadena; the program of graduate study in the two fields is essentially the same, except for specialized advanced courses. There also is close cooperation between these groups and the students and astronomers interested in planetary physics and space science.

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; chemical abundances in normal and peculiar stars; 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 the structure of the galaxy; globular clusters; gamma-ray bursts; digital sky surveys; and the physics of solar phenomena.

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 astronomy 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 Oschin and 18-inch Schmidt wide-angle telescopes, and other auxiliary instruments, together with an astrophysical laboratory on the Institute campus. Graduate student thesis research may be conducted at any of these facilities. The great light-collecting power of the 200-inch Hale Telescope permits advanced studies of the size, structure, and motions of the stars of the galactic system; of the distance, motion, and nature of remote galaxies and quasi-stellar radio sources; and of many phenomena bearing directly on the constitution of matter. The 48-inch Oschin Telescope has made possible a complete survey of the northern sky, as well as an attack upon such problems as the structure of clusters of galaxies, the luminosity function of galaxies, extended gaseous nebulae, and the stellar content of the Milky Way. A second Sky Survey is now essentially complete. These two unique instruments on Palomar Mountain supplement each other; the 200-inch Hale Telescope reaches as far as possible into space in a given direction, while the 48-inch Oschin Telescope photographs upon a single plate an entire cluster of distant galaxies or a star cloud in our own galaxy. At Palomar a 60-inch telescope owned jointly by Caltech and the Carnegie Institution of Washington was completed in 1969. It is used for photometry, spectroscopy, and photography. The Palomar telescopes have modern instrumentation and detectors designed for both optical and infrared wavelengths.

A multipurpose solar equatorial telescope has been installed at an observing station at Big Bear Lake and is now run jointly with the New Jersey Institute of Technology. The unique atmospheric conditions in this area make possible investigations of the fine structure of the solar atmosphere. Emphasis is on high-resolution spectroscopy, magnetography, and cinematography. A major effort is the study of solar oscillations.

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 six-element millimeter-wave synthesis interferometer array, a five-element interferometer for solar studies, and a 5.5-meter telescope dedicated to observations of the microwave background radiation. The 40-meter telescope is used for studies of radio sources and of the microwave background radiation. 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.

A special purpose instrument for imaging the microwave background, located in Chile, is now operational.

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. It is planned to combine them 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.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

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

Areas of Research

General areas of research represented within the option include signal transduction, cell cycle, DNA and RNA structure and metabolism, control of gene transcription during development, electron transport proteins and bioenergetics, biological catalysis, macromolecular structure, membrane proteins, and biotechnology and biomolecular engineering. More specific examples of biological phenomena currently under study include the transduction of signals received by cell surface receptors into an appropriate response, as in chemotaxis or transmission of signals across synapses in the nervous system; the replication of DNA; the biochemical

networks that control initiation and termination of cell division; the controlled transcription of DNA sequences in the genome into RNA and the processing of this RNA into mRNA and the subsequent translation into protein; the molecular mechanisms controlling the differentiation of precursor cells into specialized cells such as neurons, lymphocytes, and muscle cells; the mechanisms by which synaptic transmission in the brain is regulated during thinking and the formation of memories; the processes, driven by fundamental principles of chemical bonding and molecular energetics, by which a given linear sequence of amino acids folds into a specific three-dimensional structure in the appropriate cellular environment; how electrons move within a cell to accomplish the many redox reactions necessary for life; how light is harvested by 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.

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 biolo-

gy, developmental biology, genetics, immunology, molecular biology, structural biology, neurobiology, and virology. 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, notably the new biochemistry 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.

Physical Facilities

The campus biological laboratories are housed in six 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, and the Beckman Institute. 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, 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 and transport processes and their application in understanding, designing, and controlling a broad spectrum of complex chemical processes. The faculty and students utilize their analytical methods and resources to understand diverse processes and to synthesize new working materials and new operating strategies for improving process performance. The combination of engineering principles, chemistry, biology, and mathematics which characterizes chemical engineering at Caltech enables students and faculty to contribute to the solution of a broad spectrum of critical problems and to aid in creating emerging new high-technology industries.

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:

- *Biocatalysis:* In vitro evolution of industrial enzymes; protein adaptation to extreme environments; protein synthesis and design; theory of directed evolution.

- *Fluid mechanics and transport processes:* Mechanics of polymeric liquids, microstructured fluids, colloidal dispersions and suspensions. 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 compatible for use in living systems.
- *Catalysis:* Synthesis of molecular sieves and molecular sieve thin films. Synthesis of inorganic membranes for gas separations and catalysis.
- *Ceramics and electronic materials:* Aerosol formation of ceramic particles. Synthesis of inorganic materials and ceramics. Synthesis and characterization of quantum dots and nanostructural materials.
- *Plasma processing of electronic materials:* Etching and deposition. Dynamics of plasma-surface interactions. Modeling and simulations of pattern-dependent charging and profile evolution during plasma etching.
- *Environmental chemical engineering:* Physics and chemistry of atmospheric gases and aerosols.
- *Aerosols and colloids:* Nucleation and growth of particles. Particle formation and reactions. Structure and properties of colloidal dispersions.
- *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.

Physical Facilities

The chemical engineering laboratories, housed in the Eudora Hull Spalding Laboratory of Engineering, are extremely well equipped. The equipment includes experimental reactors, computational facilities, and NMR spectrometers, as well as numerous special research facilities for molecular graphics, DNA synthesis, and electronic, optical, and chemical measurements.

CHEMISTRY

Caltech's chemistry program offers exciting opportunities for study and research in many areas of chemical science. Eminent faculty and strong programs are available in chemical synthesis, structural chemistry, chemical dynamics and reaction mechanisms, theoretical chemistry, biochemistry, bioinorganic, bioorganic, and biophysical chemistry, materials chemistry, and molecular engineering. Active interaction exists between chemistry and other disciplines at Caltech, especially applied physics, biology, chemical engineering, environmental engineering, geological and planetary sciences, and materials science. There is strong interest on the part of the faculty in both teaching and research, and the undergraduate and graduate programs are designed to encourage the greatest possible amount of freedom, creativity, and flexibility.

Areas of Research

Caltech has long had a reputation for excellence in chemistry in the areas of molecular structure and the nature of chemical bonding. This tradition is continuing. Work in structural chemistry ranges from X-ray crystallographic structural determinations of macromolecules, covalent compounds and transition metal complexes, to investigations of the stereochemistry of organic molecules, conformations of oligopeptides, solution structures of proteins and nucleic acids, and dynamical structures of macromolecules and membrane systems. Active programs in other areas of spectroscopy include laser Raman of metalloproteins and inorganic complexes; laser spectroscopy of molecular ions and ionic clusters; ion-cyclotron resonance spectroscopy of biomolecules in the gas phase; multidimensional and multiple-pulse NMR of solids and interfaces; and scanning tunneling microscopy of semiconductors and biological systems.

Much of the current research in chemistry is directed at finding out how chemical reactions work in both chemical and biological systems. Chemical physics programs in this area include studies of gas phase reactions and processes using ion cyclotron resonance, molecular beams, and picosecond/femtosecond laser techniques. In organic chemistry, research focuses on the chemical basis of synaptic transmission; sequence-specific recognition of DNA; and mechanistic enzymology. Catalysis by transition metals is receiving emphasis among researchers in the inorganic and organometallic areas. Research in progress includes mechanisms of electrode surface chemistry and electrocatalysis, uses of transition metal complexes as homogeneous and heterogeneous catalysts, solar energy conversion and storage, water oxidation, methane oxidation, and nitrogen fixation. Reactions of molecules on surfaces are a significant focus, especially on semiconductors. A number of biochemical

projects are aimed at obtaining detailed information about reactions catalyzed by enzymes, including electron transfer reactions promoted by metalloproteins.

A significant amount of synthetic chemistry is involved in many of the above projects. In addition, several groups have chemical synthesis as a primary goal of their research. This research includes projects aimed at the synthesis of complex organic molecules of importance in biology and human medicine; new organic molecules and materials with novel electronic properties; and molecules required for the testing of structural theories. Efforts are also directed at the development of novel and synthetically useful chemical transformations. The division has a strong program in polymer science, with emphasis on the development of strategies and methodologies for the synthesis of designed polymers.

Research in biochemistry and molecular biology includes crystallographic studies of macromolecule structures, studies on the folding and stability of proteins, the mechanisms of enzyme catalysis and allosteric transitions, interactions between proteins and nucleic acids, structural elucidations of nucleic acids, studies of membrane structure and function, protein-lipid interactions, and mechanisms of ion and electron transport in biological membranes. Many of these studies make use of recombinant DNA and cloning to probe fundamental biochemical processes.

Current work in energy-related research comprises studies of laser isotope separation, photochemistry, catalysis, electrochemistry, and molecular processes for energy production, storage, and transmission.

Our theoretical chemistry program encompasses work on the applications of quantum mechanics to the study of electronic states of molecules and solids. The emphasis of the work here is on excited states and reactions of molecules, including studies of resonance-enhanced multiphoton ionization processes in molecules. Theoretical techniques are also being developed to facilitate detailed understanding of electron transfer processes, proton transfer reactions, energy randomization processes within molecules, and the dynamics of reacting systems. Computer simulations are addressing even more complicated systems, from solid-state materials to complex biomolecules.

Physical Facilities

The laboratories of chemistry consist of five units providing space for about 300 graduate students and postdoctoral research fellows. Crellin and Gates laboratories house several research groups, the divisional computing facility, the divisional High Field NMR facility, and the divisional administrative offices. Several synthetic research groups occupy the Arnold and Mabel Beckman Laboratory of Chemical Synthesis. The Braun Laboratories in Memory of Carl F and Winifred H Braun are shared with the

Division of Biology. The Arthur Amos Noyes Laboratory of Chemical Physics, one of the major research facilities, is adjoined by the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory. 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 urban development, water supply, energy generation and transmission, water treatment and disposal, transportation, and space development. Dealing with the function and safety of such facilities as buildings, bridges, pipelines, dams, rivers, 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 basic 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; soil mechanics and foundation engineering; finite element analysis; hydraulics and coastal engineering; and environmental engineering (see also environmental engineering science). 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 structural design; system identification and control of structures; structural health monitoring; the use of finite element methods for structural analysis; behavior of soil models in a centrifuge; investigation of sediment transportation and dispersion in water; turbulent mixing in density-stratified flows; wave-induced harbor oscillations; tsunamis; design criteria for various hydraulic structures; aerosol filtration; water reclamation; and ocean outfalls for discharges.

Students whose interests are in environmental problems may enroll for graduate degrees in either civil engineering or environmental engineering science.

Physical Facilities
Civil engineering activities are housed in two buildings: the Franklin Thomas Laboratory, which contains the soil mechanics laboratory and centrifuge, the earthquake engineering research laboratory and library, and the vibration laboratory; and the W. M. Keck Engineering Laboratories, which contain the laboratory of hydraulics and water resources and the environmental engineering science 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

CNS is an interdisciplinary option that studies problems arising at the interface between molecular, cellular, neural and systems biology, electrical engineering, computer science, and physics. The unifying theme of the program is the relationship between the physical structure of a computational system (physical or biological hardware), the dynamics of its operation, and the computational problems that it can efficiently solve. The creation of this multidisciplinary program stems largely from recent progress on several previously unrelated fronts: the analysis of complex neural systems, using single- and multi-unit recording techniques in combination with optical and other imaging techniques; the modeling of artificial neural networks; and analytical, numerical, and integrated electronic circuits to record from, model, and understand complex networks, including the brain. Faculty in the program belong to the Divisions of Biology; Engineering and Applied Science; and Physics, Mathematics and Astronomy. 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, computational hardware and software, and information theory.

Areas of Research
Areas of research include experimental and modeling studies of vision and the visual system on the basis of electrophysiology psychophysics, and functional imaging techniques; cognitive psychology; the circuitry, computational function, and modeling of the olfactory cortex; the analysis of olfactory coding in insects and mammals; the design and fabrication of analog VLSI for early stages in visual processing; the theory of collective neural and silicon circuits for biological and machine computations; modeling and representation of physical objects for the general analysis of images; the use of optical devices in parallel computational hard-

ware; the neuron as a computational device; computational modeling and analysis of information processing in biochemical networks; the design and use of synthetic macromolecules as computational devices; the study of evolution in natural and artificial systems; the study of the auditory system of birds; synaptic plasticity in the rat hippocampus; memory-related activity in the human hippocampus; visual motion perception, movement planning, and spatial awareness using a combination of neurophysiological, psychophysical, and computer modeling techniques; light and magnetic resonance imaging of cell lineages, cell migrations, and axonal connections in the forming nervous system; functional MRI imaging of visual cortical areas in humans and other primates; design and implementation of novel algorithms and architectures that enable efficient fault-tolerant parallel and distributed computing; and learning theory and systems, pattern recognition, information theory, and computational complexity.

COMPUTER SCIENCE

Although computing is a ubiquitous tool in all areas of study and research at Caltech, computer science is directed at the theory and technology of computation itself. Computer science is the study of information, and of the structures that communicate, store, and process information. Whether these structures are expressed in hardware and called machines, in software and called programs, or in nature or society, the fundamental concepts are similar. The student of computer science at Caltech does 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 in the physical and natural sciences, the objects of study by computer scientists are artificial systems; that is, structures that are purposefully designed, taking into account constraints imposed by our building blocks in the physical 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 also a formal or, at least, systematic one. Managing the great complexity of useful systems requires that one represent computations in a way that is amenable to mathematical treatment, as well as to 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; computer architecture; concurrent computation; theory of computation; programming languages; semantics; programming methods and correctness; the human-machine interface, including natural language; information theory; machine learning and computational finance; computer vision; computer graphics; and computer-aided design. 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, linguistics, and electrical engineering.

- *Physical Implementation of Computations.* Our 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 development, engineering, and design of very large scale integrated (VLSI) circuits, and this remains a core part of the research and education. 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 systematic design of systems at all levels. This shows up in the design of numerical algorithms for physical simulation and graphics, design of concurrent and distributed systems, abstractions for physical computing substrates, design of learning systems, the design of programming languages, and the automated optimization of computations for both software and hardware implementation. The success of computer systems has allowed us to build systems of unprecendented scale and complexities. These systems can only be understood and managed if we are careful to 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, and serve as a basis for 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.
- *Interdisciplinary Research.* Computation enables better control and understanding of the physical world. These are big themes at Caltech. We've already noted the intimate way in which computer science works 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. Further, 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. These relations provide many opportunities for scholars in computer science to work closely with colleagues throughout science and engineering at Caltech.

Physical Facilities

The computer science department has excellent computing facilities ranging from high-performance workstations to multiprocessors and supercomputers. The inventory of computers is upgraded frequently, and students have easy access to state-of-the-art equipment. The department has two semi-immersive 3-D displays and numerous graphics workstations, and it maintains VLSI laboratories equipped with complete facilities for the construction and testing of experimental systems. The department maintains several laboratories open to students and has a wide collection of software for a range of applications. 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 aeronautics), 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 identifica-

tion 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 large flexible structures; vortex structures in complex fluid flows; mixing and transport processes in fluids; classical dynamics of triatomic 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, 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, solid-state materials and devices, power electronics, control theory, signal processing, data compression, and communications.

The Lee Center for Advanced Networking sponsors a wide range of long-term research efforts in ubiquitous communications and computing technologies. Several electrical engineering faculty participate, and faculty from computer science, applied physics, control and dynamical systems, and economics are also involved.

More information is available at http://www.its.caltech.edu/~leectr/leecenter.html.

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. *Solid-State Electronics* (Nicolet)—Projects emphasize experimental research in semiconductor device technology and currently include thin-film reactions, amorphous metallic alloys for thin-film diffusion barriers, characterization of epitaxial structures and their stability under ion irradiation and thermal processing.
2. *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.
3. *Lasers and Guided Waves* (Bridges)—Experimental and theoretical studies in optical-, submillimeter-, and millimeter-wave technology and applications: EHF electro-optic modulation, dielectric waveguides and fiber optics, gas lasers; optical communication and measurement systems.
4. *Communications* (Effros, Goodman, McEliece, 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 general network reliability studies and ATM networks in particular; access, spectral sharing, dynamic channel allocation, and multiuser detection in wireless systems; 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.

5. *Microsystems* (Goodman)—Theoretical and experimental research in intelligent autonomous systems. Our goal is to design software- and hardware-based systems that exhibit intelligent decision-making behavior, using adaptive techniques such as learning and evolution. The integration of swarm-intelligence principles inspired by social insects, and the use of neuromorphic sensors are key strengths of the lab. Specific research topics are collective autonomous robotics; machine learning and neural networks; probabilistic modeling methods; and analog, digital, and neuromorphic VSLI processing. Current projects in neuromorphic chip design include "the silicon nose"—an electronic olfaction chip—and "the active skin"—an integrated micromachined chip (for reducing drag on an aircraft wing), which combines sensors, actuators, and a neural network controller. Current projects in collective autonomous robotics include distributed sensing (odor, vision, etc.) strategies for exploring and mapping unknown environments, freeway traffic safety algorithms, and distributed strategies for manipulating and building 2-D structures. Current projects in swarm intelligence and machine-learning algorithms include the development of adaptive control strategies for autonomous robots, robust dynamic routing in telecommunication networks, graph partitioning in VLSI, and multiagent software strategies for autonomous searching and business transaction on the Web. Experimental work is done in a dedicated robotics arena and lab, which provides a fleet of 24 autonomous robots of different sizes (from 2 cm to 30 cm in diameter) and capabilities (from PIC microcontrollers to PC104-based Linux architectures), together with computer vision tracking equipment. Hardware- and software-development facilities take place in the microsystems lab, and include robot simulators (Webots), VLSI design facilities, and a wide variety of instrumentation and hardware test equipment.
6. *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.

7. *Wireless Engineering* (Hajimiri, Rutledge)—Circuits and system design for wireless communication using integrated circuit technology, including 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. These building blocks are used in the design of complete transceiver circuits with new architectures for various applications. We also have interests in devices for radar, remote sensing, broadcasting, and industrial power from 1MHz to 1THz. Current projects include phased-array radars, quasi-optical amplifiers and oscillators for millimeter-waves, multiplier grids for 1THz and high-frequency Class-E amplifiers. For more information see http://www.its.caltech.edu/~mmic/group.html.
8. *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.
9. *Optical Information Processing* (Psaltis)—Research to develop optical techniques and devices for information processing. Current areas of interest include optical memories, optical neural computers, neural network models of computation, pattern recognition and image processing, photorefractive crystals, liquid crystals, and Si optoelectronic devices.
10. *Microsensors and Microactuators* (Tai)—Silicon micromachining technology is used to fabricate miniature solid-state microelectromechanical devices. Current research includes pressure sensors, flow sensors, IR sensors, accelerometers, microphones, micromotors, microvalves and micropumps, neuro-probes, and microsurgical tools. Device research requires broad exercise covering physics, design, fabrication, and testing. Hands-on training is especially emphasized in our Micromachining Laboratory.
11. *Digital Signal Processing* (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, efficient signal coding and data compression, adaptive signal processing, mul-

tidimensional multirate systems, and wavelet transforms. Digital filter banks, subband coding, multidimensional multirate signal processing. Image processing, digital halftoning, and denoising.

12. *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. Emphasis on multiscale image analysis; analysis of motion sequences for navigation, control, and reconstruction of ambient geometry; 3-D photography, perception, and modeling of shapes; visual object recognition; vision-based human-computer interfaces; perception and modeling of biological motion. Areas of collaboration include learning theory, computer graphics, neurophysiology, psychology, applied probability, robotics, geometry, and signal processing.
13. *Nanofabrication and Design of Ultrasmall Devices* (Scherer)—High-resolution lithography and dry etching allow the miniaturization of structures to below 10 nm. 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.
14. 1. *Parallel and Distributed Computing* (Bruck)—Theoretical and experimental research on a number of fundamental issues related to the design of novel algorithms, protocols, and architectures that enable efficient parallel and distributed computing for scientific and commercial applications. Special emphasis on creating and experimenting with novel communication algorithms and protocols for reliable and efficient interprocessor communication over a variety of communication media, including communication subsystems of parallel machines and local area networks. Also includes research on new models for computing inspired by neural networks with emphasis on the questions: What are the essential ingredients that make real neural networks computationally powerful? Can we improve computing systems based on these insights?
    2. *Fault-Tolerant Computing*—Research on fault-tolerance aspects of high-performance computing systems. The focus is on the underlying theory as well as the practical challenges, including the creation of checkpointing schemes for scientific and commercial applications, the design of reliable communication algorithms and interconnection architectures, and the development of schemes based on error-correcting codes to enable reliable storage and high-bandwidth communication. More information can be found at http://paradise.caltech.edu/.

15. *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, multimedia communication systems, packet-based communication systems (such as the World Wide Web and digital cellular phone systems), and distributed data storage systems. Areas of investigation include the theory and practice of optimal data compression for inhomogeneous data sets (universal source coding); systems in which the available rate varies as a function of system or user variation (multiresolution source coding); data representations for packet-based systems with nonzero probability of packet loss (multiple description source coding); combined information representation and communication systems (joint source and channel coding). Techniques employed in these systems include entropy coding, vector quantization, transform coding, subband coding, bit allocation, and motion compensation. Results include new source coding paradigms, theoretical performance bounds, rate of convergence results for universal codes, and practical code design algorithms. The research combines ideas from information theory, signal processing, and optimization. Possible areas of collaboration include communications, wireless communications, distributed computing, digital signal processing, and computational vision.
16. *Integrated Circuits* (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 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.

ENGINEERING SCIENCE/BIOENGINEERING

The option of engineering science has developed as new frontiers of engineering have advanced to coalesce with major disciplines of science such as geophysics, environmental science, and biology. Since its inception, this option has served as a common ground in

developing synergism among various disciplines of engineering and science at Caltech. Advanced programs of study leading to the degrees of Master of Science and Doctor of Philosophy in engineering and applied sciences are offered through the ES option.

In recent years, due to remarkable advances in measurement and control technology, as well as MEMS and computer sciences, new opportunities for applying engineering techniques to biological and biomedical problems have emerged.

From its fundamental level (molecules) to integral units of the human body, the field of biology is becoming more accessible to engineering approaches. Examples include the development of optical tweezers in handling molecules, and superefficient mechanical heart valves. Another set of examples is new medical imaging techniques that, in conjunction with exciting novel applications of robotic microsurgery and neural prostheses, provide better diagnosis and prognosis for treating many life-threatening diseases.

The new emphasis on bioengineering within the option of engineering science is intended to produce a new generation of engineers who can, through Caltech's fine tradition of fundamental, interdisciplinary education in science and technology, push forward the frontiers of bioengineering and biomedical fields.

Areas of Research

The main active areas of research in bioengineering by the associated faculty include:

- Biomaterial engineering;
- Tissue engineering;
- Cardiovascular fluid dynamics;
- Microfluidic devices;
- Robotics technology for minimally invasive surgery;
- Neural prostheses;
- Optical trapping and manipulation of molecules and particles;
- Wave effects in biomechanics (shock wave lithotripsy and remote spinal injury);
- Biomechanics of the musculoskeletal system;
- Biomimetics (mechanophysiology of swimming, walking, undulating, and flying);
- Transport phenomena in biological systems; and
- Biological and biomedical imaging.

The ES option continues to host a broad range of other subjects that include research topics such as vortical flows, wake phenomena, aerosol physics, and free surface flows.

Physical Facilities

Research work in bioengineering is primarily carried out in the associated faculty laboratories. Please consult the bioengineering Web site for a detailed list of the laboratories and the research activities in each.

ENVIRONMENTAL ENGINEERING SCIENCE

This interdisciplinary graduate program is concerned with the science and engineering of environmental systems. Research and instruction emphasize basic scientific studies that underlie new solutions to challenging environmental problems such as urban, regional, and global air quality; water supply and water quality control; hazardous waste treatment; microbial ecology; and global environmental change.

Among the academic disciplines central to the program are atmospheric and aquatic chemistry; environmental fluid mechanics; applied microbiology; dynamic meteorology; hydrology; aerosol physics and chemistry, chemical reaction engineering, and chemical kinetics. Courses are offered in the environmental engineering science 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; chemistry of the mineral-water interface; coagulation and filtration of particles; advanced oxidation processes for water treatment; biogeochemical cycling of arsenic; disinfection of water; aerosol chemistry and physics; cloud chemistry and global climate change; measurement of free radical species in the stratosphere and upper troposphere; photochemistry of important trace gases; novel treatment processes for hazardous materials, e.g., ultrasound, pulsed-power plasmas, semiconductor photochemistry; environmental photochemistry; oxidation processes in aqueous systems; pollutant and particle transport in alluvial streams and groundwaters; the interaction of long waves with the shoreline; studies of the emissions sources and fate of organic chemicals in the atmosphere; regional air pollution modeling and control; effects of air pollutants on works of art; global-scale modeling of tropospheric chemistry; marine geochemistry; microbiology of arsenic in natural waters; and microbiology of iron-reducing organisms.

Physical Facilities

The laboratory experimental work in environmental engineering science is primarily carried out in the W. M. Keck Laboratories with a wide variety of modern instrumentation in the various laboratories described below.

The Air Quality Laboratory includes a facility located on the roof of Keck that has been specially designed for studies of the

photochemical reactions of gaseous and particulate pollutants. A large (60 m^3) outdoor chamber is used for direct simulations of atmospheric conditions using carefully prepared mixtures of hydrocarbons, nitrogen oxides, and other pollutants. Both gas phase chemistry and the formation of aerosol particles are probed with this system. A smaller (1 m^3) artificially illuminated chamber is used primarily for studies of chemical mechanisms and product identification. Analytical instrumentation includes monitors for major pollutants, 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).

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.

Through the Center for Interdisciplinary Remotely Piloted Aircraft Studies, a collaboration between Caltech and the Naval Postgraduate School in Monterey, California, a small aircraft that can be operated either piloted or remotely piloted is available for studies of the chemical, physical, and meteorological properties of the lower troposphere.

The environmental chemistry and aquatic chemistry laboratories and the Environmental Analysis Center are equipped for chemical analysis by atomic absorption, polarography, 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 hydraulics laboratory has a variety of water channels and basins appropriate for studies of waves, sediment transport, turbulent diffusion, and density-stratified flows. A 40-meter-long glass-walled flume is equipped with dual circulating water systems for density-stratified shear flow studies. This tilting flume can also be used as a wave tank to generate breaking waves using a computer-operated hydraulic wave generator. Two smaller wave flumes also have computer-controlled wave generators that can produce waves of specified profiles. Four multibeam laser-Doppler velocimetry systems are available for velocity measurements in turbulent flow studies or for wave-induced fluid velocity measurements. High-resolution laser-induced fluorescence is used for simultaneous concentration measurement, and mass flux and dispersion studies. The laser systems can be directly coupled to a laboratory computer system that can accomplish real-time multiuser processing and experiment control with data presentation by video graphics or hard-copy plotter. Additional computers are available for data analysis.

The applied microbiology laboratory includes a facility for the preparation of bacterial media, as well as equipment for large- and small-scale culture, continuous culture, DNA isolation and manipulation, DNA sequencing and sequence data manipulation, protein purification and enzyme assays, and field sampling and analyses. In addition, access is available to the electron microscope facility on campus, as well as the oligonucleotide probe synthesizer and the microprotein sequenator.

The department provides students with access to scientific computing and word processing through various departmental and personal computers and advanced supercomputers operated by the Institute.

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 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. Interdisciplinary studies are encouraged and students may carry out academic and research programs within and between different divisions.

The geographical position and geologic setting of the Institute are favorable for year-round field access to a wide variety of earth

problems and materials. Current advances in understanding the dynamic motions of the earth's crust and the structure of the interior have opened new opportunities for research into the processes responsible for the earth's development and activity. Seismic activity in the Southern California area presents stimulus and research material for the study of earthquakes, which are of great practical concern and are intimately related to the earth's development on a global scale. Human records of seismic activity are put into long-term perspective by studies of surface and bedrock geology, which reveal the history of motion on fault systems. The dynamics and geometry of crustal movements are studied by geological and geophysical methods on both planetary and local scales in order to understand the evolution of continents. Major processes and events in the chemical and physical evolution of the earth can be identified by studying the structure of rocks formed or modified in these events, and their chemical and isotopic compositions. The absolute chronology can be established by measurements of radioactive isotopes. A wide variety of studies focuses on the origins of igneous and metamorphic rocks in planetary interiors. These include radiogenic and stable isotopes and experimental petrology, in addition to field and petrographic studies. The broadscale structure of the earth is inferred from isotopic-geochemical studies and is interrelated with geophysical studies. Further breadth in our understanding of the earth and its place in the cosmos is being gained by the comparative study of the other planets—their atmospheres, surfaces, and internal structures. The early history of the solar system can be approached by studies of lunar samples and meteorites. The earliest solar and presolar history is being studied by seeking the connection between the residual planetary materials and the physical-chemical processes within the solar nebula and the precursor interstellar medium.

Physical Facilities

The division is housed in three adjacent buildings, which are well equipped for modern instruction and laboratory work. They contain several comfortable seminar rooms and the library as well as student and faculty offices. Numerous computer capabilities are distributed throughout the division, including a facility for geographic information systems, remote sensing, and 3-D modeling. There is an analytical facility (which includes an electron microprobe, a scanning electron microscope, and X-ray diffraction equipment). There is a machine shop for the design and fabrication of experimental equipment. Specimen collection and sample preparation areas are available. There are modern laboratories for the chemical analysis of solids, liquids, and gases. A variety of mass spectrometers (electron impact, thermal ionization, laser ablation, ion microprobe, and inductively-coupled plasma) provide analyses at the trace and ultralow levels. Optical, infrared, and Raman spec-

troscopies are available for the characterization and analysis of samples. State-of-the-art tunable far-infrared and infrared laser spectrometers are available for the study of gas phase and surface processes of importance in cosmochemical and geochemical environments. This facility is used to study the mechanisms of chemical reactions that govern the formation of the protosolar nebula and the earth's upper atmosphere. Laboratories for experimental petrology contain high-temperature furnaces and presses for work up to more than 20 GPa. In addition, there is a laboratory for the study of the behavior of rocks and minerals and their elastic constants in the pressure and temperature environments of planetary interiors. This includes a shock-wave laboratory for studying ultra-high-pressure equations of state and shock effects.

Conditions for field study and research in the earth sciences in Southern California are excellent. A great variety of rock types, geologic structures, active geologic processes, physiographic forms, and geologic environments exist within convenient reach of the Institute. The relatively mild climate permits field studies throughout the entire year; consequently, year-round field work is an important part of both the educational and research programs. There are active field programs in diverse areas in North America and throughout the world.

The Seismological Laboratory of the Institute is housed in the Seeley G. Mudd Building. This has excellent computer facilities and maintains a seismological observatory, which includes the Kresge Laboratory, located about three miles west of the campus on crystalline bedrock, affording a firm foundation for the instrument piers and tunnels. The Seismological Laboratory carries on a vigorous program of geophysical research and education and is headquarters for a modern 200-station broadband array called TriNet. This array provides an excellent research facility for the study of earthquakes and earth structure.

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. Planetary science minicomputers and image processing systems are linked, through the campus network, to the Image Processing Laboratory at JPL and to supercomputers across the country. In addition, Caltech owns and operates several optical and radio observatories that are used partly for planetary research. A particularly active program of planetary studies is pursued at the Owens Valley Radio Observatory.

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.

HUMANITIES

Literature at Caltech spans the major periods of American, British, and European writing. Students can pursue interests ranging from Latin literature to a survey of drama; from Shakespeare 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 human knowledge and judgment. At Caltech, particular emphasis is placed on philosophy of the natural and social sciences, moral and political philosophy, and philosophy of psychology. Members of the faculty have a variety of other interests, including philosophical problems of policy analysis and the history of philosophy. Courses 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 literature faculty, interested in new approaches to studying their subject, engage in research into the relationships between literature and psychology, 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; politics and culture in the American West; the history of the physical and biological sciences and of science in relationship to society; history and film; political and economic development in early modern Europe; and Chinese history and demography. A cluster 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 and psychology, 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 200.)

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, 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 aeronautics, 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, crystalline alloys containing chemical disorder, nanocrystalline materials, proton-conducting solid acids and perovskites, and ceramic-metal composites. The physical characteristics of interest span a wide range of mechanical, thermodynamic, and electrical properties. Materials science is a cross-disciplinary field, and materials research is performed by groups in many different options at Caltech. Graduate students in the materials science option can perform their thesis research with a supervisor or cosupervisor in a different option.

Physical Facilities
Research by the faculty, graduate students, and a few advanced undergraduates is conducted in the W. M. Keck Laboratory of Engineering Materials. Material-preparation facilities include equipment for physical vapor deposition under ultrahigh vacuum

conditions, shock-wave consolidation of powders, rapid solidification, equipment for the processing of ceramic powders, high-energy ball milling, and ion-beam modifications of materials. Facilities for the characterization of materials include an extensive array of X-ray diffraction equipment including a single crystal diffractometer, two X-ray powder diffractometers with high-performance, position-sensitive detectors, a small-angle X-ray scattering system, impedance spectrometers for transport and dielectric measurements, a Rutherford backscattering spectrometer, Mössbauer spectrometers, two differential scanning calorimeters and two differential thermal analyzers, cryogenic facilities for the characterization of superconductors, and several test systems for the measurement of mechanical properties. A modern microscopy facility has been built around a Philips EM 430 300-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 interest in this discipline. The main active areas of research by the faculty include the following:

- *Algebra:* finite group theory, algebraic K-theory.
- *Algebraic Geometry:* Hodge theory, moduli spaces, arithmetical geometry.
- *Analysis:* classical real and complex analysis, complex dynamics, fractals, harmonic analysis, operator theory, and functional analysis.
- *Combinatorics:* combinatorial designs, matrix theory, and coding theory.
- *Geometry and Topology:* low-dimensional topology, hyperbolic geometry, geometric group theory, and foliations; symplectic geometry and topology, their applications to mathematical physics.
- *Mathematical Logic:* set theory, and its interactions with analysis and dynamical systems.
- *Mathematical Physics:* Schrödinger operators.
- *Mathematical Statistics:* sequential analysis, decision theory.
- *Number Theory:* algebraic number theory, automorphic forms, and Galois representations.

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, seminar rooms, a lecture hall, and a lounge for informal gatherings of the students and staff. Sloan Laboratory also houses a reference library in mathematics. The main mathematics library with its outstanding collection of journals is housed nearby in the Robert A. Millikan Memorial Library.

ITS, Information Technology Services, provides general purpose computing facilities and internet services for the Caltech community. Computing equipment is also available in the mathematics computer laboratory on the second floor of Sloan Laboratory.

MECHANICAL ENGINEERING

Mechanical engineering at Caltech is focused at the interfaces 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, 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). These areas are applied to a rich diversity of problems including bioengineering, 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, pollution control, 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.* Studies in the field of mechanics may be undertaken in either the applied mechanics, mechanical engineering, or civil engineering options. In general, work pursued within the mechanical engineering option will emphasize aspects of mechanics that concern active materials, MEMS, and thin films.
- *Mechanical Systems and Engineering Design.* Activities in mechanical systems and engineering design encompass a broad range of traditional mechanical engineering fields, such as 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. In the abstract, engineering design is the rigorous application of theory and analysis from traditional engineering disciplines to the synthesis of novel solutions to new problems. Analytical techniques from many fields are used to analyze the performance, stability, and robustness of complex systems. An imaginative, practical approach is emphasized for the solution of real problems involving many areas of technology. 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 Applied Fluid Mechanics.* 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, acoustics of turbulent flows, two-phase flow, cavitation, turbomachines for flow of liquids and rocket propellants, and air pollution.
- *Jet Propulsion.* The Daniel and Florence Guggenheim Jet Propulsion Center provides facilities for postgraduate education and research in jet propulsion and advanced spacecraft propulsion. Students wishing to pursue courses of study and research in jet propulsion take degrees in aeronautics or mechanical engineering. The program generally emphasizes basic subjects (such as combustion, two-phase flow, turbomachinery, and acoustics) that are applicable to a wide variety of engineering problems. The experimental facilities of the Jet Propulsion Center are located in the Karman Laboratory of Fluid Mechanics and Jet Propulsion. A collaborative program in advanced propulsion exists with NASA's Jet Propulsion Laboratory.

Physical Facilities
Laboratory facilities are available in a number of areas, including control of mechanical systems, computer-aided design, heat transfer, liquid phase turbomachines, thin-film deposition, pump dynamics, 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. The Engineering Computing Facility (ECF) is available for computational studies.

PHYSICS

Areas of Research
Graduate students in physics will find opportunities for research in the following areas where members of the staff are currently active.

- *Particle Physics.* Experiments in elementary particle physics are carried out with accelerators at the European Center for Nuclear Research (CERN), Cornell, and Beijing. Activities include studies of Z° decay at the LEP storage ring at CERN, studies of charmed quarks and τ leptons at IHEP, and studies of τ leptons at Cornell. In addition, a large project to search for magnetic monopoles and other phenomena in particle astrophysics is under way at the Gran Sasso underground laboratory in Italy. An active program is aimed at a future experiment to study CP-violation and rare B decays at a new accelerator at SLAC.
- *Kellogg Radiation Laboratory.* Studies of the structure and interactions of nuclei currently include experiments in the few-MeV energy range, carried out with Caltech's in-house tandem electrostatic accelerators, and experiments in the multi-GeV range, carried out at SLAC, CEBAF (Virginia), the Bates Linear Accelerator Center (MIT), and DESY (Hamburg, Germany). The lower-energy studies are designed to address important problems in nuclear astrophysics, while the high-energy studies emphasize the effects of the quark structure of nucleons on the structure and properties of nuclei. The group is active in research involving polarized and cryogenic targets that support the experimental program.
- *Nuclear and Neutrino Physics.* This group focuses on fundamental properties of nuclei and elementary particles, particularly neutrinos. Experiments on neutrino oscillations being carried out at the San Onofre nuclear reactor and on double beta decay in an underground laboratory in the Gotthard tunnel in Switzerland help us understand neutrino mixing and neutrino mass. The experimental program, which also includes symmetry tests with polarized nuclei using a dilution refrigerator, is complemented

by theoretical studies of nuclear structure and particle properties.

- *Experimental High-Energy Astrophysics.* Research in this field encompasses X-ray and gamma-ray astronomy, compact object and gamma-ray burst astrophysics, cosmic-ray astrophysics, and magnetospheric and heliospheric physics. The Space Radiation Laboratory (SRL) is actively developing new instrumentation for hard X-ray and gamma-ray balloon and satellite experiments which will study compact objects, Active Gallactic Nuclei, gamma-ray bursts, and supernova remnants. An observational program concentrated on high-energy observations of neutron star and black hole systems using the Compton Gamma-Ray Observatory, the ROSAT and ASCA X-ray satellites, and the X-ray Timing Explorer is also a major effort in the group. SRL is also using instruments developed for launch on spacecraft and balloons to measure the composition of energetic nuclei arriving from the sun, the local interstellar medium, and nearby regions of the galaxy in order to study how these nuclei were synthesized and accelerated to high energies. There are a total of five SRL instruments currently active on Voyager, Galileo, and SAMPEX missions, with two or more to be launched on the Advanced Composition Explorer in 1997. The SAMPEX and Galileo missions are also supporting studies of trapped radiation in the magnetospheres of Earth and Jupiter, while the Voyager instruments are approaching the solar wind termination shock.
- *Experimental Ultraviolet and Optical Astrophysics.* A sounding rocket program is developing novel telescopes and detectors for mapping the far cosmic ultraviolet background. New spectroscopic techniques are being exploited to study the dynamics and ionization of the violent interstellar medium. Ground- and space-based observations are being made to study the halos of galaxies, the history of star formation in the universe, the nature of UV bright objects, and the evolution of supernova shock waves in a heterogeneous interstellar medium. The first far UV all-sky imaging survey mission is currently under study. A new ground-based instrument for diffraction-limited imaging is being developed for the Palomar 5-meter telescope.
- *Infrared Astronomy.* Astrophysical observations from 1-micron to 1-millimeter wavelengths are carried out with ground-based telescopes at the Palomar and Keck observatories. The infrared group constructs instruments for use on the 5-meter Hale and 10-meter Keck telescopes. Caltech has been a major participant in a survey of the infrared sky conducted by the IRAS satellite.
- *Submillimeter Astronomy.* Star formation, interstellar gas, galaxies, and quasars are studied using the 10-meter telescope at the Caltech Submillimeter Observatory on 14,000-foot Mauna Kea in Hawaii. Far-infrared observations are made from NASA's Kuiper Airborne Observatory. Research is conducted on super-

conducting tunnel junction and bolometer detectors for use in future telescopes, both on the ground and in space.

- *Computational Astronomy.* High-performance parallel computers are applied to computation-intensive problems in astronomy. Topics include radio pulsar searches, diffraction limited imaging with ground-based optical/IR telescopes, and large N-body simulations.
- *Condensed Matter Physics.* Two-dimensional matter, phase transitions in two and three dimensions, phonon physics, and high-temperature superconductivity are areas of interest. Extensive new facilities for nanostructure fabrication and ultra-low-temperature physics have been established in Sloan Laboratory for exploration of mesoscopic systems. These facilities are complemented by the Microdevices Laboratory of the Jet Propulsion Laboratory (JPL), which plays a central role in a number of collaborative research efforts. Very recently, a new effort has been launched on the fractional quantum Hall effect and other strong correlation phenomena in semiconductor heterostructures.
- *Applied Physics.* Techniques of theoretical and experimental physics are applied to problems in surfaces, materials, and planets. Work is done with on-campus facilities, including ion accelerators and UHV thin-film preparation equipment, as well as off campus, at both industrial and other academic laboratories. Recent studies include sputtering, damage by high-energy ions, modification of semiconductors by ion implantation, the behavior of granular materials, and light-emission mechanisms in phosphors and scintillators.
- *Quantum Optics.* Investigations of quantum dynamical processes in nonlinear dissipative systems are carried out in a number of fundamental optical experiments. Specific areas of research include the generation and application of squeezed and antibunched states of light, the realization of ideal quantum measurement and amplification schemes, and the investigation of nonperturbative radiative processes in cavity quantum electrodynamics. Facilities in support of this work are located in the East Bridge Laboratory.
- *Experimental Gravitational Physics.* Efforts are focused upon establishing a Laser Interferometer Gravitational-Wave Observatory (LIGO), which is currently under construction. The LIGO Project conducts research and development in precision measurement techniques and their application to gravitational-wave astronomy. On-campus research facilities include the 40-meter interferometer, special laboratory facilities for optics, vacuum studies, and electronics development, and an extensive network of computer workstations. The experimental program is complemented by work in the theoretical astrophysics group.

- *Neuroscience.* Some properties of neural networks that underlie brain function are being investigated. The emphasis is on studies of neuronal networks grown in tissue culture, whose activity and response to stimuli are recorded as they change in response to imposed patterns of activity. Advanced biophysical and bioengineering technologies are used to obtain long-term electrical and optical records of neural signals.
- *Theoretical Physics.* The particle theory group studies the unification of interactions based on superstring theory, the properties of hadrons described by QCD with an emphasis on heavy quarks, the quantum properties of black holes, and quantum cosmology. Theoretical studies also include nuclear structure and reactions, condensed matter physics, including the quantum theory of solids and turbulent fluids, and various aspects of mathematical physics.
- *Theoretical Astrophysics.* Many astrophysical interests are pursued in collaboration with the astronomy faculty, including problems in general relativity and cosmology, in relativistic astrophysics and accretion theory, in the interstellar medium, in the dynamics of stellar and planetary systems, in helioseismology, and in quasars, pulsars, and neutron stars.

Physical Facilities

The physics department is housed in six buildings grouped together on the south side of the 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 Synchrotron Laboratory. Members of the staff also carry out research at the Palomar Observatory and at the Owens Valley Radio Observatory. Several computers are available for use in research, including the Intel Touchstone DELTA System, a high-performance supercomputer with a peak speed of 30 Gflop.

Caltech has been a major participant in several infrared astrophysics missions and projects, including data processing support for the Infrared Astronomical Satellite (IRAS) mission, and the 2MASS ground-based 2-micron all-sky survey in conjunction with the University of Massachusetts. Caltech has been selected to develop and manage the Space Infrared Telescope Facility (SIRTF) Science Center, which will support science operations for the SIRTF Observatory scheduled for launch in December 2001.

SCIENCE, ETHICS, AND SOCIETY/HISTORY AND PHILOSOPHY OF SCIENCE

The program in science, ethics, and society is devoted to understanding the evolution of science and technology and their interactions, past and present, with the larger society. The program integrates historical, philosophical, and technical studies to explore the development and practice of the physical and biological sciences since the 17th century. Considerable attention is paid to the social, economic, political, and institutional context of technical development, particularly how the demands and organizations of industry, government, and philanthropy have shaped the scientific and technological enterprise. The program also examines the related moral and ethical issues—religious, social, and otherwise—that have pervaded disputes in areas such as weapons research and arms control, biotechnology and biomedicine, the environment, and scientific misconduct.

Areas of Research
Historical research in the program covers a broad range of subjects, including central developments in the fields of modern physics and physical chemistry, genetics and molecular biology, the sciences of mind, and special subjects such as the history of Big Science, federal policy for research and development, the political economy of patents, scientific instruments, biotechnology, and the environment. Philosophical research in the program deals with issues in causality and scientific inference, mind and the development of language, philosophy of psychology, foundations of probability and risk assessment, bioethics, and scientific fraud and misconduct. All research in the program is conducted in a multidisciplinary environment that ties together past and present as well as history, philosophy, politics, and economics. Work in science, ethics, and society may be pursued as an undergraduate option and minor, a graduate minor, or on a course-by-course basis.

SOCIAL SCIENCE

Social science at Caltech offers a unique program closely integrating the fields of economics, law, political science, and quantitative history. The program takes a practical but rigorous approach to social science—designing institutions to solve problems—and involves extensive use of empirical techniques and mathematical modeling. Particular emphasis is placed on studying the relationships between economics, politics, and public policy in a rigorous scientific manner. Students can use their considerable quantitative talents to great advantage in these areas.

Areas of Research

The social science program is characterized by collaborative interdisciplinary research on the behavior of, and methods to improve the performance of, political and economic institutions.

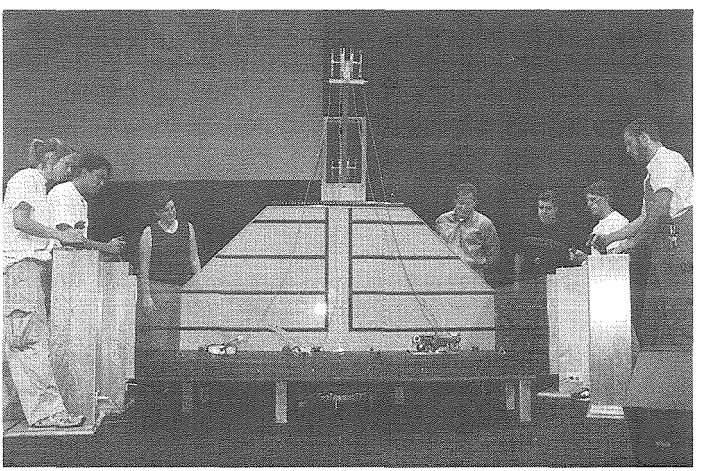
Among the areas of research in political science are statistical analyses of campaign dynamics and the effect of economic conditions on voting, and theoretical models of legislative behavior and international relations.

Quantitative history incorporates economic and political models with statistical analysis to address such issues as the extent of racial discrimination in the United States, and the role of capital markets in economic growth.

Economists study problems such as the design of institutions for the efficient provision of public goods, with applications to such diverse problems as railroad rights of way, space shuttle resources, and the telecommunications industry. There is also interdisciplinary research on improving the theoretical and statistical models of individual choice behavior.

Caltech is a major center for the experimental investigation of game theory as a basis for economic and political decision making, and the application of these methods to public policy.

Information for Undergraduate Students



REQUIREMENTS FOR ADMISSION TO UNDERGRADUATE STANDING

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 I and three subject exams, SAT II; teacher and counselor evaluations; personal characteristics; a demonstrated interest in math, science, or engineering; and information provided on the application.

Applying

An application for admission may be obtained by writing or calling the Office of Undergraduate Admissions, California Institute of Technology, Mail Code 55-63, Pasadena, California, 91125, (626) 395-6341. To be considered for admission, applications to the freshman class must be postmarked by January 1.

Early Action

Students who have a preference for Caltech may want to consider application under the Early Action plan. The Early Action application process requires that the completed application be postmarked by November 1. Under this application plan, students will be notified in late 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
(calculus or higher is strongly recommended)
One year of physics (calculus-based physics is recommended)
One year of chemistry
Three years of English (four years are recommended)
One year of U.S. history/government

College Board Tests

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 I: Reasoning (Verbal and Mathematical)
SAT II: Writing
SAT II: Math II C
One of the following SAT II subject exams: 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 writing to the appropriate address. Applicants who wish to take the examinations in the western United States or Canada, or in Mexico, Australia, or the Pacific Islands should write the College Board, P.O. Box 23060, Oakland, CA 94623-2306. For all other inquiries, write the College Board, P.O. Box 592, Princeton, NJ 08540.

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

Three evaluations and a Secondary School Report are required. One must be from a math or science teacher, one from a humanities or social science teacher, and one from an additional evaluator (see the instructions in the application), and a Secondary School Report must be filled out by your high-school counselor or other school official. You may submit more than required, but at least one must be submitted in each category.

Additional Information

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 social security number.

Acceptance

Caltech is a College Board member and therefore agrees to comply with the candidate's reply date of May 1. When accepting an offer of admission to Caltech, an admitted student is required to submit a nonrefundable matriculation fee of $250, along with the matriculation form. Places in the entering class will not be held after May 1. Early Action applicants will be informed of their status in late 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 programs. However, college credit for these classes is not automatic. Course credit and/or placement in an accelerated program is *sometimes* granted as deemed appropriate by the department faculty. The awarding of Caltech course credit takes place at the time of registration each fall.

Biology
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.

Chemistry
In exceptional cases, students with a particularly strong background in chemistry may elect to take Chemistry 21, the Physical Description of Chemical Systems, or Chemistry 41, Chemistry of Covalent Compounds, rather than Chemistry 1, General and Quantitative Chemistry. It is assumed that such students have reasonable competence in the following areas: 1) elementary theories of atomic structure and electronic theories of valence, 2) chemical stoichiometry, 3) computations based upon equilibrium relation-

ships, and 4) elementary chemical thermodynamics. 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 qualification for advanced placement in chemistry will be determined by performance on a placement examination to be administered in the summer prior to registration and on subsequent approval by the instructors of the courses to be taken and the courses to be substituted. 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).

Mathematics

Normally, an entering freshman will take Ma 1 abc, Probability and Calculus of One and Several Variables. This course will cover the calculus of functions of one and several variables; basic probability; vector algebra; basic linear algebra; derivatives of vector functions, multiple integrals, line and path integrals, theorems of Green and Stokes; and infinite series. The course will be divided into a lecture part, discussing primarily the mathematical notions, and a recitation part, providing active practice in the application of mathematical techniques.

During the summer, entering freshmen will be asked to take a diagnostic exam in basic calculus and, when appropriate, will be invited to outline their advanced training in mathematics and take a placement examination. The appropriate course and section for each student will be determined on the basis of this information. Those students whose preparation permits them to begin with Ma 2 a will receive credit for Ma 1 abc. Exceptionally well-prepared students may receive additional credit for Ma 2 ab. Students in need of additional background in elementary calculus 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 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 to help 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 and a number of the upperclass students and the 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, SAT I scores, 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.

Freshman courses:

Math 1 abc
Physics 1 abc
Chemistry 1 ab
Chemistry 3 a
Biology 1
Humanities and Social Science electives

Sophomore courses:

Math 2 ab
Physics 2 ab
or
Physics 12 abc
Menu science class (currently either Ay 1 or Ge 1; can be taken freshman or sophomore year)
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 as a degree-seeking student, 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 must submit SAT I: Reasoning (Verbal and Mathematical) scores. If the SAT I has not been taken previously, it must be taken no later than the April sitting. International students are also expected to take the SAT I, which is administered by the College Board. Transfer applicants living in countries in which the SAT I is not offered may be considered for admission, but should be aware that the lack of SAT I scores will weaken their application.

The TOEFL (Test of English as a Foreign Language) is required of transfer applicants who are not citizens or permanent residents of the United States, and whose native language is not English. The TOEFL should be taken by the February sitting. International students who have studied in the United States for more than two years are exempt from taking the TOEFL.

Transfer Admissions Entrance Examinations

All applicants are required to take Caltech Transfer Admissions Entrance Examinations in mathematics and physics. An additional exam in chemistry is required of those students planning to study chemistry or chemical engineering. 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 March 1. Applicants will be notified of the decisions of the Admissions Committee in mid-June. Questions about transfer admission and application should be directed to Transfer Information, Office of Undergraduate Admissions, Caltech Mail Code 55-63, Pasadena, CA 91125, U.S.A., (626) 395-6341.

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)
Grinnell College (IA)
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, Scripps 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.

In addition, through the office of the dean of students, informal exchange programs are conducted with several colleges and universities throughout the country. Under these programs, a student can visit another campus for a period ranging from one term to a full academic year, without the formalities of transfer proceedings or written applications. Any student interested in the informal program should check with the dean of students for details.

CALTECH CAMBRIDGE SCHOLARS PROGRAM

The Caltech Cambridge Scholars Program offers qualified juniors and seniors the opportunity to spend a fall or winter term at Cambridge University in England. Students are hosted by and live in one of the Cambridge Colleges participating in the exchange. The participating colleges are Corpus Christi, Pembroke, St. Catharine's, and St. John's. During their term at Cambridge, students take three to five lecture or module courses. The number of

courses depends on Cambridge departmental requirements. For this work, students receive 36 units of Caltech general or option credit. 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 apply in February for the next academic year. Further information, including application procedures and the exact application deadline date (the first Friday in February), is available from the Fellowships Advising and Study Abroad Office.

Please see page 157 of the Financial Aid section of the *Catalog* for details on applying and eligibility for financial aid related to study abroad.

ROTC

Through arrangements with the University of Southern California (USC), Army and Air Force Reserve Officers' Training Corps programs are available to all qualified full-time Caltech students. Two-, three-, and four-year Air Force Reserve Officers' Training Corps (AFROTC) programs are available. Academic units earned in this program may be counted as elective units toward Caltech graduation requirements. Scholarship opportunities, which pay up to full tuition plus books, fees, and a $200 monthly allowance, are available for academically competitive students. Students in the last two years of the program automatically qualify for $3,500 per school year. Successful completion of the AFROTC program, upon graduation, leads to a commission as a Second Lieutenant with subsequent active duty service in the Air Force. Applicants to AFROTC must have at least two years remaining toward degree conferral, which may include graduate study. Entry into the last two years of AFROTC is on a competitive basis. Students have the option of attending AFROTC classes at the University of Southern California, Harvey Mudd College in Claremont, or CSU San Bernardino. Interested students may obtain more information by contacting the AFROTC program office at USC at (213) 740-2670.

The Army ROTC program at USC offers four-, three-, and two-year scholarships that pay tuition costs up to $20,000 a year. In addition, the program pays all contracted cadets a stipend of $1,500 a year and an annual book allowance of another $450. 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 lieu-

tenant 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 for further information to contact the Department of Military Science at the University of Southern California: PED 110, Los Angeles, CA 90098, (213) 740-1850.

REGISTRATION REGULATIONS

Procedures

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

- returned a signed registration card with their approved study list, *and*
- made satisfactory arrangements with the Bursar's Office for the payment of all fees due the Institute.

Any student who has not completed both phases of registration within one week after registration day 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 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 Undergraduate Academic Standards and Honors Committee that no petitions for the retroactive dropping or adding of courses will be considered except under very extenuating circumstances.

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, 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 approved by the director of health services or the director of counseling services. Return from a leave for medical reasons also requires the recommendation of the director of health services or the director of 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 approval from the director of health services or the director of 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 designee). Nothing in this statement precludes access to the normal student grievance procedure.

All other petitions pertaining to leaves should be addressed to the Undergraduate Academic Standards and Honors Committee.

Withdrawal from the Institute

Formal separation from the Institute is effected by filing a completed withdrawal card with the registrar. The effective date of an immediate withdrawal is the date of the signature of the dean or associate dean of students. 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. Reinstatement rules are the same as those listed under scholastic requirements. A student must withdraw by the last day

of classes in any term. No courses or grades for that term will appear on the permanent record of the student. However, the date of withdrawal and the number of units will be noted on the record. The record will also indicate whether an undergraduate student sabbatical was granted.

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 permanent record card; the grade of F will be recorded for all other courses.

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 file a registration card for such summer work in the registrar's office 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.

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 Registration Day 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 registration by the Undergraduate Academic Standards and Honors Committee. Freshmen who have accumulated 24 or more units of E or F, or 3 or more course grades of E or F, exclusive of PE, are ineligible to register for subsequent terms and must petition the Committee for reinstatement if they wish to continue as students. The dean of students or the associate dean may act on the petition if the student has received fewer than 42 units of E or F, exclusive of PE. For other petitions, action can be taken only by the Committee. Freshmen who have been reinstated will be ineligible to register if in any subsequent term of their freshman year they obtain 6 or more units of E or F, exclusive of PE. In this situation,

action can be taken only by the 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, 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 permanent record card 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 Undergraduate Academic Standards and Honors 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 will be acted upon 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 Undergraduate Academic Standards and Honors Committee for action. *All subsequent reinstatements must be acted upon by the Committee.* In any case being considered by the Committee, students may, if they wish, appear before the Committee or, on request by the Committee, they may be required to appear. A second reinstatement by UASH will be granted only under exceptional conditions.

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
At the end of the spring term a student will be declared ineligible to register if he or she has not completed 99 units in the three most recent terms of 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.

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. As a general rule this second degree must be in an option which is not in the same division as that of the original 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 Committee on Undergraduate Academic Standards and Honors. 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 with 27 or more units may be approved by the dean or associate dean if the student has not previously had an underload. Seniors may take an underload by presenting for the registrar's approval a course plan for graduation the following June, provided that the plan does not require an overload in any term. In all other cases the student must petition the Undergraduate Academic Standards and Honors Committee for approval. The

committee has the latitude to grant part-time status to a small number of exceptional, highly motivated students with at least junior standing, for reasons deemed valid by the committee.

Miscellany

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 advanced placement credit upon admission, credit will not be granted for Caltech courses not registered for, 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.

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.

In exceptional circumstances an undergraduate 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.

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.

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" for complete details.)

ATHLETICS AND PHYSICAL EDUCATION

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. *Of this 9-unit PE requirement, only 3 units may be counted from PE 1.* 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. Enrollment in classes is conducted during registration. Late regis-

tration 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. Participation in intramural sports will count toward the successful completion of an instructional class of the same activity.

UNDERGRADUATE EXPENSES

For freshman and transfer students applying for admission, there is a $50 application fee. This fee is nonrefundable.

A nonrefundable matriculation fee of $250 for freshman and transfer students is payable upon notification of admission. Housing contracts must be submitted to the director of residence life by the date specified in the instructions accompanying the contract.

Expense Summary 2000–2001

General:		
General Deposit	$ 100.00	[1]
Tuition	19,743.00	
Student Body Dues, including the *California Tech*	60.00	[2]
Assessment for the *Big T*	36.00	[2]
Assessment for Caltech Y	$ 15.00	
	$ 19,954.00	
Other:		
Student Housing: (Rates are subject to change)		
Room (on campus; other rates vary)	3,597.00	
Board (provides 10 full meals and five continental breakfasts per week while Institute is in session)	2,583.00	
Dues	105.00	
Books and Supplies (approx.)	900.00	
Personal Expenses (approx.)	1,650.00	
Meals not on Board contract (approx.)	$ 1,686.00	
	$10,521.00	

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

[2] *Fees subject to change by action of the Board of Directors of the Associated Students of the California Institute of Technology.*

The following is a list of undergraduate student fees at the California Institute of Technology for the academic year 2000–2001 together with the dates on which these charges are due. Fees are subject to change at the discretion of the Institute.

First Term
September 18, 2000 (Freshmen)
September 25, 2000 (All Others)

	Fee
General Deposit	$ 100.00
Tuition	6,581.00
Associated Student Body Dues	20.00
Assessment for *Big T*	12.00
Assessment for Caltech Y	5.00
Room and Board (for on-campus residence)	2,060.00
Student House Dues and Assessment	35.00

Second Term
January 2, 2001

Tuition	$ 6,581.00
Associated Student Body Dues	20.00
Assessment for *Big T*	12.00
Assessment for Caltech Y	5.00
Room and Board (for on-campus residence)	2,060.00
Student House Dues and Assessment	35.00

Third Term
April 2, 2001

Tuition	$ 6,581.00
Associated Student Body Dues	20.00
Assessment for *Big T*	12.00
Assessment for Caltech Y	5.00
Room and Board (for on-campus residence)	2,060.00
Student House Dues and Assessment	35.00

Tuition Fees for fewer than normal number of units:

36 units or more	*Full Tuition*
Per unit per term	$ 183.00
Minimum tuition per term	1,830.00

Audit Fee $183 per lecture hour, per term.

Other Items of Interest

Refunds and Repayments
Students withdrawing from Caltech may either be entitled to a refund or required to make a repayment.

For those students receiving no financial assistance, the institutional charges, e.g., tuition and fees, room and board, books and supplies, will be prorated according to the number of days the student actually attended Caltech before withdrawing (see withdrawal information below). These prorated charges will be compared to the payment the student has made and the student will either receive a refund or owe an amount to Caltech.

For those students receiving funds from federal Title IV, and/or Caltech, and/or state programs, the Institute will use specific procedures to determine the amount of 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 spent in academic attendance. If the amount of aid disbursed to the student is greater than the amount the student earned, unearned funds must be returned. If the amount the student was disbursed is less than the amount the student earned, the student is eligible to receive a postwithdrawal disbursement.

The Department of Education has provided a summary of these regulations in *The Student Guide* for the 2000-2001 award year, available on-line at www.ed.gov/prog_info/SFA/StudentGuide/.

Determining the Student's Last Date of Attendance or Withdrawal Date: The Office of the Registrar is responsible for receiving a request for a withdrawal from the appropriate 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; or
- The date the student otherwise provided official notification to the registrar (written or oral) of his or her intent to withdraw; or
- The mid-point of the academic term if no official notification is provided; or
- The date determined by the registrar if there are special circumstances (illness, accident, grievous personal loss); or
- The date the registrar determines began a leave of absence if the student does not return from an approved leave or if the student does not qualify for a leave of absence.

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 Office of Financial Aid 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% of the student's federal financial aid in accordance with federal procedures, as well as Caltech and/or state grants/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% of the period, he or she earned 100% of the aid for the period. If the student completed 60% or less, the percent age 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 Office of Financial Aid and/or the Graduate Office (as appropriate) will allocate the return of funds back to the student aid programs in the order of the following:

1. Federal Unsubsidized Stafford Loan Program;
2. Federal Subsidized Stafford Loan Program;
3. Federal Direct Unsubsidized Stafford Loan Program;
4. Federal Direct Subsidized Stafford Loan Program;
5. Federal Perkins Loan Program;
6. Federal PLUS Loan Program;
7. Federal Direct PLUS Loan Program;
8. Federal Pell Grant Program;
9. Federal SEOG Program;
10. 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, please contact the Office of Financial Aid, 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 may 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: Should a student, for whatever reason, withdraw 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 student 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. This policy is consistent with the philosophy of financial aid being utilized after the resources of the student and parents. Refunds of tuition are given only through the first half of the academic term, while the room and board refunds are prorated for the entire academic term less forfeiture of any housing deposits.

A different refund policy is required if the student is the recipient of federal Title IV student assistance. For first-time students at Caltech, a pro rata refund is required through the 60 percent point

of the term. Any refund must then be applied first to the federal aid program(s) in the following prescribed order:

1. Federal SLS
2. Federal Unsubsidized Stafford Loan
3. Federal Subsidized Stafford Loan
4. Federal PLUS Loan
5. William D. Ford Federal Direct Unsubsidized Stafford Loan
6. William D. Ford Federal Direct Subsidized Stafford Loan
7. William D. Ford Federal Direct PLUS Loan
8. Federal Perkins Loan
9. Federal Pell Grant
10. Federal Supplemental Educational Opportunity Grant
11. Other federal Title IV aid programs
12. Other federal sources of aid

Any remaining refund will then be returned to other state, institutional, or private student assistance utilized.

If the student is the recipient of federal Title IV student assistance, but is not a first-time student, a comparison of institutional refund policy (previously mentioned) and a federal methodology (called Appendix A) must be made, and the policy giving the greatest refund to be applied to the federal aid programs is to be used. Again, refunds are applied first to the federal aid programs in the prescribed order. The federal methodology of Appendix A is as follows:

	refund to the student's account
Start of term to 10% point of the term	90%
Between 10% and 25% point of the term	50%
Between 25% and 50% point of the term	25%
After 50% point of the term	0%

Specific examples of refund calculations are available upon request.

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.

ASCIT Dues

As a service to the Associated Students of the California Institute of Technology, Inc., or ASCIT, dues of $60 per year and an assessment of $36 for the college annual, the *Big T*, are collected by the Institute and turned over to ASCIT. A subscription to the student newspaper, the *California Tech*, is included in these dues, and the balance is used in the support of student activities as deemed appropriate by the ASCIT Board of Directors. Students not wishing to join ASCIT or to purchase the *Big T* should so indicate at the time of registration.

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 returned the necessary forms 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 Board of Control decision may be collected through the Bursar's Office, at the request of the dean of students.

Student Houses
Students in the houses must supply their own blankets. Bed linens and towels are furnished and laundered by the Institute.

Application for rooms in the student houses may be made by addressing the Director of Residence Life, 115-51, California Institute of Technology, Pasadena, CA 91125.

Special Fees
Students taking the Summer Field Geology course (Ge 120) 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 term following that in which the past due charges were incurred. Transcripts will not be released until all bills have been paid or satisfactory arrangements for payment have been made 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 and fees, room and board, an allowance for meals not covered in the board contract, books and supplies, personal expenses, and a travel allowance based on airfare for two round trips. (Caltech is unable to include a travel allowance for students whose residence is outside the United States, Mexico, or Canada.) 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. Most students who attend Caltech qualify for some kind of financial aid from the Institute, federal and state agencies, outside organizations such as foundations and businesses, and/or lending institutions. Assistance offered by Caltech includes federal, state, and institutional grants, low-interest loans, and subsidized jobs. U.S. citizens or eligible noncitizens (as defined in the application) 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. 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 157 and 160–167.)

All students who believe they will need assistance to attend Caltech are encouraged to submit financial aid applications to the Financial Aid office. Application procedures are outlined below.

The Financial Aid staff is happy to talk with students and their families at any time to explain the application process and Caltech's computations. For further information on the determination of financial need and on application procedures, as well as on financial aid awards and programs, contact the Office of Financial Aid, California Institute of Technology, Mail Code 12-63, Pasadena, CA 91125, call (626) 395-6280, or visit the Caltech Financial Aid office home page at http://www.finaid.caltech.edu/.

Slightly different procedures and deadlines exist for each category of student applying for financial aid. Detailed descriptions of these procedures and deadline dates may be found on the Caltech Financial Aid office Web site at http://www.finaid.caltech.edu/.

Incoming Student Application Process for Caltech and Federal Financial Aid PROFILE

The College Scholarship Service (CSS) PROFILE application and the Free Application for Federal Student Aid (FAFSA) forms are both required of all applicants (with the exception of international applicants, who should review the specific procedures listed on page 138) for Caltech need-based assistance. These forms provide essential information about the applicant's family's financial picture and enable the Financial Aid office to determine eligibility for federal, state, and Caltech financial assistance.

Please note the following steps for filing the PROFILE and FAFSA forms:

Step 1

To receive a 2001–2002 PROFILE application, students may register by connecting to the College Board Online at http://www.collegeboard.org/ or by telephoning 1-800-778-6888, beginning September 15. This number is available Sunday through Friday, 8:00 a.m. to 10:00 p.m. (Eastern time). Students registering by telephone will have the option of paying PROFILE fees by credit card or being invoiced for check/money order payment at the time of application submission. Those filing on-line must be prepared with credit card information. The customized PROFILE application packet will be mailed within 24 to 48 hours of the student's phone call. The electronic customized PROFILE application is available on-line within minutes of registering.

Step 2

Complete the customized PROFILE application and submit it to CSS for processing. CSS will then report the financial information to the colleges listed on the Registration form and mail each student a Data Confirmation Report (DCR) approximately 2 to 3 weeks after receipt of the PROFILE application.

Step 3

Students must also complete the Free Application for Federal Student Aid (FAFSA) in early January. The FAFSA is available in paper version from your high school. The Internet version of the FAFSA is available after January 1, 2001, at http://www.fafsa.ed.gov/. Complete the FAFSA with Caltech's code 001131 and submit according to the schedule below. The completed FAFSA form is

required to determine eligibility for federal and state financial aid programs. As with the PROFILE, it is advisable to estimate income information in order to meet the priority deadline.

CALTECH'S FINANCIAL AID PRIORITY MAILING DATES

Type of Applicant	*Register for PROFILE by*	*Submit PROFILE Application by*	*Submit FAFSA by*	*Receive conditional aid award information by*
Early Action Applicant	October 16	November 15	January 15	February 1
Other Freshman Applicants	December 15	January 15	January 15	April 16
Transfer Applicants	January 15	March 2	March 2	June 15
Continuing 2001–2002 CIT Students	Not applicable	Not applicable	March 2	Summer

International Applicants
International applicants will be sent the Foreign Student Financial Aid Application along with their application for admission.

INTERNATIONAL STUDENT
FINANCIAL AID PRIORITY MAILING DATES

Applicants	*Mail Completed Foreign Student Financial Aid Application to Caltech by*
FRESHMAN INTERNATIONAL	March 2
TRANSFER INTERNATIONAL	April 16
CONTINUING CIT INTERNATIONAL	March 2

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 aid for any other academic period while they are undergraduates at the Institute. Citizens of Canada and Mexico are exempt from this rule. Those offered financial aid will be eligible to apply for aid in subsequent years.

All students must reapply for aid each year.

TYPES OF AID AVAILABLE

Once financial need has been determined, that need will be met either by a single type of aid or by a combination of grants or scholarships, student employment, and low-interest loans. Such a combination is called a financial aid "package."

Grants and scholarships, which include those provided both through Caltech and by the federal and state governments, do not have to be repaid. Employment wages are funds earned during the academic year either on or off campus. Employment opportunities exist for students who wish to work to help meet their educational costs. Loans are a sound means of meeting a portion of current educational expenses by borrowing against future earnings. Loans, of course, must be repaid.

Disbursement of Funds

Financial aid funds are disbursed depending on the type of aid and its source:

Caltech grants, scholarships, and merit awards, as well as state and federal grants, are automatically credited to the student's account, in equal amounts, at the beginning of each academic term.

Federal Perkins Loans, Direct Stafford Loans, and Caltech Loans, are also credited each term, in equal amounts, to the student's account.

- Federal Perkins and Caltech Loans require that the borrower complete a Borrower Data Sheet and sign a promissory note for each loan disbursement. These forms are available at the Bursar's Office during fee payment each term.
- Federal Perkins Loan borrowers must read and sign an Entrance Interview form.
- Federal Direct Stafford Loan borrowers must attend an Entrance Interview and must sign an Entrance Interview form prior to receiving their loan. The Entrance Interview is also available on-line at http://www.ed.gov/offices/OPE/DirectLoan/.

Paychecks (for actual hours worked) from Federal Work Study and CIT Work Study earnings are disbursed to students at the work site on a biweekly basis.

Outside scholarships are disbursed according to the sponsor's specifications. If the funds are sent to the Financial Aid office, they will be credited to the student's account.

Note: For information on Federal Direct PLUS loan disbursements, please see page 148.

Grants and Scholarships

Caltech Grants are gifts awarded from an institutional fund or endowment specifically established for the purpose of assisting undergraduates. The amount of the award depends entirely on demonstrated financial need and is subject to available funds. Caltech Grants are renewable based on demonstrated financial need, which is assessed annually when students apply for financial aid.

"Named" scholarships are awarded to undergraduates from money given by individuals or organizations for scholarship purposes and are "named" by or for the donor. All aid applicants who meet the specifications of the donor are considered for a "named" scholarship. No special application need be filed. Since many donors are lifelong friends of the Institute and enjoy hearing about student life at Caltech today, recipients may be asked to write a thank-you letter to one or more donors. Named scholarships are given in lieu of Caltech Grants.

Federal and State Grants

The Federal Pell Grant Program is for undergraduate students who have not yet completed a baccalaureate degree. Eligible students may receive Federal Pell Grants for the period of time necessary to complete a first undergraduate baccalaureate degree.

The Federal Pell Grant program is intended to be the "floor" of the student's financial aid package. This is usually the first program for which a student's eligibility is determined. Many other federal aid programs require that a student's Federal Pell Grant eligibility be considered prior to determining eligibility for other aid. Application for a Federal Pell Grant is made by using the *Free Application for Federal Student Aid (FAFSA)*. Applicants will receive a Student Aid Report (SAR) directly from the FAFSA processor. Upon receipt of the SAR, students should review it for accuracy. If corrections need to be made, students can submit the SAR to the Financial Aid office for corrections.

If eligible, the exact amount of the student's award will be determined by the Financial Aid office based upon the cost of attendance, the expected family contribution, and the student's enrollment status.

In 2000–2001, Pell Grant awards will range up to $3,300 per year.

The Federal Supplemental Educational Opportunity Grants (FSEOG) Program provides grant funds for undergraduate students who have not completed their first baccalaureate degree and who are financially in need of this grant in order to pursue their education. Awards of FSEOG funds must be made first to students who show exceptional financial need (defined as those students with the lowest federal expected family contribution at the Institute).

Priority for FSEOG funds must be given to Pell Grant recipients. No additional application is required. These grants are contingent upon federal appropriations. The minimum annual FSEOG award is $100, and the maximum annual award is $4,000.

Cal Grants are awarded to California residents by the California Student Aid Commission (CSAC). All students who are eligible to apply are required to do so each year at the time they apply for Caltech assistance. Students should complete a FAFSA and GPA Verification Form. Results from the FAFSA are sent by the processor to the CSAC, where eligibility is determined. Renewal materials are mailed to current recipients at their permanent addresses each year in December. Students must renew their Cal Grant eligibility on an annual basis by completing the FAFSA. The FAFSA deadline for new applicants is March 2.

Cal Grant A, which is awarded on the basis of financial need and academic achievement, is designed to assist with the cost of tuition and fees. In 1999–2000, the Cal Grant A awards ranged from $7,164 to $9,420.

Cal Grant B is awarded to students from disadvantaged/low-income families. During the first year, Cal Grant B recipients are awarded a monthly stipend for living costs. Renewal Cal Grant B recipients are awarded the monthly stipend and, in addition, assistance with tuition and fees. In 1999–2000, Cal Grant B recipients received a maximum of $1,410 total in quarterly stipends and a range of $7,164 to $9,420 in tuition and fee assistance.

Many other states provide scholarships and grants. A complete list of state scholarship agencies and their addresses is available from the Financial Aid office. Students should contact the agency in their states of residence regarding programs available and application procedures.

Self-Help: Employment and Loans

A self-help award is a combination of loans and employment opportunities available during the academic year to help meet school expenses. Students often can choose how much of their self-help they wish to earn and how much they wish to borrow.

The amount of self-help expected of a student is established yearly by the Institute. For the 2000–2001 academic year, a freshman typically was awarded $6,575 ($5,000 loan and $1,575 work) toward educational expenses. An eligible student is first awarded a combination of work and/or loan, with any remaining need being met with grant assistance.

At Caltech, in order to meet their expected self-help contribution, students are offered a suggested combination of loan and employment opportunities. Students often can choose how much they wish to earn and how much they wish to borrow, or they may decide to work or borrow less than the standard self-help amount. These choices will not affect the amount of their grant.

Employment

Work programs offer students a double incentive—earning money to help meet college expenses plus gaining valuable job experience. In the competitive job market, employers look for applicants who have work experience with their education.

Student employment is generally available to all students regardless of whether they apply for financial aid. Interested students should contact the Caltech Career Development Center. Undergraduate students must receive approval from the dean of students to work more than 16 hours per week. Students typically work an average of 10 hours per week. Freshman students may not work during fall term. In subsequent terms they must receive permission from the dean of students to work before accepting their first work assignment.

The Federal Work Study Program provides jobs for eligible students who demonstrate need for such earnings to meet a portion of their educational expenses. Jobs may be located on campus or off campus. The employer may be Caltech; a federal, state, or local public agency (such as Caltech's Jet Propulsion Laboratory); or a private nonprofit organization, such as a community service agency. Beginning with the 1994–95 school year, Caltech placed an increased emphasis on placing Federal Work Study students in community service jobs. Federal Work Study employees are paid at least the federal minimum wage rate.

The maximum amount of Federal Work Study wages that students may earn is determined by financial need. To locate a job, the student may contact the campus Career Development Center and the student newspaper. *Summer Federal Work Study* may also be available.

The Caltech Work Study Program is funded by the Institute to provide part-time employment for international students who have demonstrated financial need. This program is limited to the campus or JPL. The program is designed to parallel the Federal Work Study Program, and the same guidelines apply to its administration. Summer Caltech Work Study Program funding may also be available.

Loans

Loans are a valuable resource for many students and their families in financing a college education. Loans allow students to postpone paying a portion of their education costs until they complete their education or leave school. Loan repayment generally extends up to 10 years after students graduate or leave school.

Federal Perkins Loans are awarded by the Institute to students with demonstrated financial need. Funds are obtained from the federal government and from former Caltech students who have repaid or are in the process of repaying their loans. No interest is charged on the loan while a student maintains at least a half-time

academic load. Repayment begins nine months after leaving school or dropping below half-time status. Interest is then charged at a rate of 5 percent on the unpaid balance. Federal Perkins Loans are limited to a total of $4,000 annually during undergraduate study, a total of $20,000 for all years of undergraduate study, and a maximum of $40,000 for the entire undergraduate and graduate career. Students may be allowed up to 10 years to repay, based upon the amount they have borrowed. A typical repayment chart is shown on the Caltech Financial Aid Information home page (located at http://www.finaid.caltech.edu/). Information concerning deferment, repayment, postponement, and cancellation will be provided on each borrower's loan promissory note and in a disclosure statement given to students prior to disbursements of the loan.

Caltech and Institute Loans are made from funds provided by many sources, and are used to supplement the Institute's Federal Perkins Loan funds. Generally, no interest is charged and no repayment of principal is required while a student maintains a continuous course of study as an undergraduate at Caltech. Repayment begins nine months after leaving school or dropping below half-time status. For Caltech Loans, interest is then charged at a rate of 5 percent on the unpaid balance until the loan has been repaid in full. Institute Loans are interest-free. As with Federal Perkins Loans, if the student transfers to another institution or attends graduate school, no payments need be made on the principal or interest as long as half-time attendance is maintained. More specific information is provided to each borrower on the promissory note and in a disclosure statement given to students prior to disbursement of the loan. For example, *Cecil L. Killgore Student Loans* are available to members of all undergraduate and graduate 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.

The *Federal Direct Student Loan Program* is an opportunity for students to borrow money from the federal government to pay for a Caltech education. Under this program, the U.S. Department of Education makes loans, through Caltech, directly to students. Caltech will use the Federal Direct Loan to pay tuition and fees, as

well as room and board charges, and will give any remaining money to the student for personal expenses. Federal Direct Loans simplify loan repayment—payments go directly to the federal government.

Direct Loans include:
1. the Federal Direct Stafford Loan Program;
2. the Federal Direct Unsubsidized Stafford Loan Program;
3. the Federal Direct PLUS Loan Program; and
4. the Federal Direct Consolidation Loan Program.

Federal Direct Stafford Loan
The Federal Direct Stafford Loans (subsidized and unsubsidized) are available to both graduate and undergraduate students. The federal government "subsidizes" a loan by paying the interest while the student is in school, during the grace period, and during periods of deferment. For an unsubsidized loan, the government does not provide the subsidy; therefore, interest on the loan accrues during those periods. The calculated family contribution is taken into consideration when determining a student's need for a subsidized loan. To determine eligibility for an unsubsidized loan, the family contribution is not considered. Other than these two differences, the provisions of the Federal Direct Stafford Loan Program apply to both subsidized and unsubsidized loans (i.e., loan limits, deferment provisions, etc.).

Before Caltech can determine loan eligibility, a determination of the student's eligibility for a Federal Pell Grant must be made. In order to make this determination, the applicant must complete a Free Application for Federal Student Aid (FAFSA). Subsidized Federal Direct Stafford Loans may not be used to substitute for the federally calculated expected family contribution; however, Federal Direct *Unsubsidized* Stafford Loans may be used in this capacity. Before a student can apply for a Federal Direct Unsubsidized Stafford Loan, eligibility for a subsidized loan will be determined. To reiterate, Federal Direct *Unsubsidized* Stafford Loan borrowers are not required to demonstrate need in order to be eligible. However, if the student is eligible for a *Subsidized* Federal Direct Stafford Loan, he or she will be awarded that loan first, and this award will be taken into consideration when determining eligibility for the Federal Direct Unsubsidized Stafford Loan. The amount borrowed under the subsidized and unsubsidized loans combined may not exceed the annual/aggregate loan limits, or the total cost of education.

The following chart summarizes loan limits for Federal Direct Stafford Loans and Federal Direct Unsubsidized Stafford Loans.

Maximum Loan Amount for a Full Academic Year

	Dependent Student	*Independent Student*
	Maximum combined subsidized & unsubsidized Federal Direct Stafford Loan	*Maximum combined subsidized & unsubsidized Federal Direct Stafford Loan*
1st year undergraduate	$2,625	$6,625
2nd year undergraduate	$3,500	$7,500
3rd & 4th year undergraduate	$5,500	$10,500
Graduate/Professional	N/A	$18,500

Note: The loan amounts listed above cannot exceed the cost of the student's education minus other financial aid received.

Aggregate loan amounts are $23,000 for dependent undergraduates, $46,000 for independent undergraduates, and $138,500 for graduate and professional students (including Stafford amounts borrowed as an undergraduate).

All loans must be disbursed in at least two installments. Further, loan disbursements for first-time, first-year undergraduate borrowers may not be released to the student until he or she has been enrolled in his or her program of study for at least 30 days.

The maximum interest rate for new loans is 8.25 percent. The actual rate is variable, and is determined according to a formula linked to the 91-day Treasury-bill rate. For the 2000–2001 academic year, the rate will be set in early summer 2000. To offset the federal government's cost of the Federal Direct Stafford Loan program, the borrower must pay an up-front origination fee of 4 percent of the principal amount of the loan.

Federal Direct PLUS (Parent) Loan Program

Under the Federal Direct PLUS Program, parents of dependent undergraduate students may borrow up to the difference between the cost of attendance and all other financial aid, per dependent student. Federal Direct PLUS loans are also limited to parent borrowers who have "no adverse credit history," as determined by the Secretary of Education. Federal Direct PLUS loans may be used to replace the expected family contribution. There is no cumulative maximum limit that can be borrowed under the Federal Direct PLUS program. Federal Direct PLUS loan amounts are credited to the student's account and are disbursed in equal installments each term.

Interest rates on Federal Direct PLUS loans are variable, linked to the 91-day Treasury-bill rate, but may not exceed 9 percent. For

the 2000–2001 academic year, the interest rate will be set in the summer of 2000. There is no federal interest subsidy on Federal Direct PLUS Loans. However, the government is authorized to charge the borrower an up-front origination fee of up to 4 percent to offset the federal government's cost of the program.

Unless the *parent* borrower qualifies for one of the deferments under the Federal Direct Stafford Loan Program, repayment of principal and interest must begin 60 days after final disbursement. Parent borrowers who qualify for deferment may pay interest only, beginning 60 days after disbursement, unless interest is capitalized (i.e., deferred and added to the loan principal).

Applications for Federal Direct PLUS loans are available from the Caltech Financial Aid office. Applications must be returned to the Financial Aid office for eligibility certification and processing.

Repayment Plans

Under the Direct Loan program, student borrowers have four types of repayment plans available:

1. the Standard Repayment Plan;
2. the Extended Repayment Plan;
3. the Graduated Repayment Plan; or
4. the Income Contingent Repayment Plan.

The plans vary in a number of ways to meet the different needs of individual borrowers. The following information describes these plans and provides suggestions on how to choose among them.

Standard Repayment

Minimum monthly payment	$50
Maximum number of monthly payments	120 (10 years)

Under this plan no more than 120 monthly payments are required, and for small loan amounts, the number of monthly payments can be less than 120. Each monthly payment will be at least $50, and may be more if necessary to repay the loan within 10 years (excluding periods of deferment or forbearance). The number of monthly payments will be adjusted to reflect changes in the variable interest rate. This means that as the rate varies, the monthly amount will remain the same unless the borrower requests that the repayment amount be changed.

Extended Repayment

Minimum monthly payment	$50
Maximum number of monthly payments	see table below

Loan Amount and Maximum Number of Monthly Payments for the Extended and Graduated Repayment Plans

Amount of Debt		*Maximum number of*
At least	*Less than*	*Monthly Payments*
$ 0	$10,000	144
10,000	20,000	180
20,000	40,000	240
40,000	60,000	300
60,000		360

Under this plan, the maximum number of months that payments are due (excluding periods of deferment and forbearance) depends on the loan amount. Each monthly payment will be at least $50 and may be more if necessary to pay off the loan in the maximum number of repayment months. The number of monthly payments will be adjusted to reflect changes in the variable interest rate. This means that as the rate varies, the monthly amount will remain the same unless the borrower requests that the repayment amount be changed.

Graduated Repayment

Minimum monthly payment	$25
Maximum number of monthly payments	see table above

Under the Graduated Repayment Plan, payments are lower at first and will increase over a period of time that varies depending on the amount borrowed. The minimum monthly payment is the larger of 50 percent of the amount that would be required under the Standard Repayment Plan or the amount of interest that accrues monthly on the loan. The maximum number of months the borrower will pay excludes periods of deferment and forbearance and depends on the loan amount (see table above). With this plan the monthly payment amount during the earlier portion of the repayment period is reduced. Later in the repayment period, the monthly payment amount will increase, but will never be more than 150 percent of the amount required by the Standard Plan. The monthly repayment amount is increased (graduated) every two years. The number of monthly payments will be adjusted to reflect changes in the variable interest rate. This means that as the rate varies, the monthly amount will remain the same unless the borrower requests that the repayment amount be changed.

Income Contingent Repayment

Minimum monthly payment:	Generally none (in certain circumstances, $15—see below)
Maximum number of monthly payments	300 months (25 years)

Federal Direct PLUS Loans and Federal Direct PLUS Consolidation Loans are not eligible for Income Contingent Repayment (ICR).

Effective July 1, 1996, borrowers who enter repayment will pay an amount based on the Adjusted Gross Income (AGI) they report on their federal tax return, or, if they submit alternative documentation of income, they will pay an amount based on current income. If the borrower is married, the amount he or she will pay will be based on the borrower's income and the spouse's income.

Under this ICR Plan, the borrower will pay the lesser of

1. the amount one would pay if he or she repaid his or her loan in 12 years multiplied by an income percentage factor that varies with annual income, or
2. 20 percent of the borrower's discretionary income, which is the AGI minus the poverty level for the family size.

If the borrower is in his or her first year of repayment, he or she will be required to submit alternative documentation of current income (that is, other than IRS-reported AGI) to the Department of Education. He or she will probably be required to submit alternative documentation in the second year of repayment also. Such documentation includes pay stubs, canceled checks, or, if these are unavailable, a signed statement explaining income sources. The reason for this requirement is that if the borrower filed a tax return for years that included time while in school (and probably not working full-time), the AGI the department would receive from the IRS would be unlikely to reflect current income.

If the borrower is not in his or her first year of repayment, he or she may still be required to submit alternative documentation of income if the AGI is not available or if the AGI does not reasonably reflect current income. In addition, the borrower may choose to submit alternative documentation of current income, if special circumstances, such as loss of employment for the borrower or his or her spouse, warrant an adjustment to the monthly payment.

Please note that if the borrower is married and submits alternative documentation of income for any of the reasons discussed above, he or she will also be required to submit alternative documentation for his or her spouse.

If the borrower's income is less than or equal to the poverty level for the borrower's family size, the monthly payment will be zero. If the calculated monthly payment is greater than zero but less than $5, the borrower will be required to make a $5 monthly payment. If the monthly payment is calculated to be more than $5, he or she will be required to pay that calculated amount.

The total AGI of both the borrower and his or her spouse (if married) will be used to calculate the monthly payments under the ICR Plan. The borrower will be required to provide his or her spouse's written consent to disclose tax-return information. Further, if the borrower submits alternative documentation as

noted above, he or she will be required to submit alternative documentation of spouse's income.

If the borrower's spouse has a Direct Loan, he or she can repay loans jointly. The repayment will be based on the joint income. While one is not required to repay loans jointly, it is important to remember that if only one spouse chooses to repay under the ICR Plan, the Department of Education will use the AGI (or alternative documentation of income) of the borrower and his or her spouse to determine the monthly payments.

Choosing a Repayment Plan

In selecting a repayment plan, there are several factors to understand before making a decision.

The *Standard Repayment Plan* has a shorter repayment term than under the other plans. This means the loan is paid off more quickly, and the amount of interest paid will be less than if the other plans were selected. However, the Standard Repayment Plan requires higher monthly payment amounts. If one will be able to pay a higher monthly amount, the Standard Repayment Plan may be best. If the higher repayment amount would be difficult or uncertainty exists about income level, one of the other repayment plans may be best.

The *Extended or Graduated Plan* features a longer repayment term. As a result, the monthly payment is lower than under the Standard Plan (unless the minimum monthly payment applies), but more interest over the life of the loan will be repaid. Under the Extended Plan, the payments are fixed amounts and less interest is paid than under the Graduated Plan.

The *Income Contingent Repayment Plan* features monthly repayment that will vary with the borrower's income. When income is low, one probably will have a longer repayment period than under one of the other repayment plans. As a result, a greater amount of interest is repaid over the repayment period but it may be easier to keep up with the monthly payments. If the borrower's income grows, the monthly repayment amount increases. This would reduce the repayment period and result in repaying a smaller total amount of interest over the repayment period. If the borrower's income is high and he or she chooses to limit the monthly repayment to the amount he or she would be required to pay if the loan was repaid over 12 years in equal monthly installments, the repayment period is extended, which results in more total interest paid. However, this also helps to ensure that one's payment will be manageable.

If a consistent monthly payment amount is important throughout the repayment period, select either the Standard or the Extended Plan. On the other hand, if the borrower's income is expected to increase as time passes, it might be preferable to make smaller loan payments at first and larger payments later in one's career. If so, select the Graduated Repayment Plan.

Examples of Debt Levels, Beginning Monthly Payments, and Total Amounts Repaid for All Direct Loan Repayment Plans[1]

	Standard		Extended		Graduated		Income Contingent[2]											
							Income = $15,000				Income = $25,000				Income = $45,000			
							Single		Married/HOH[3]		Single		Married/HOH[3]		Single		Married/HOH[3]	
Initial debt when loan enters repayment	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*	*Per month*	*Total*
$ 2,500	$ 50	$ 3,074	$ 50	$ 3,074	$ 25	$ 4,029	$ 17	$ 5,927	$ 17	$ 5,910	$ 23	$ 4,462	$ 22	$ 4,514	$ 28	$ 3,799	$ 28	$ 3,808
5,000	61	7,369	55	7,893	35	8,655	35	11,853	34	11,853	46	8,925	44	9,028	56	7,599	56	7,616
7,500	92	11,039	82	11,839	53	12,982	52	17,780	50	17,730	69	13,387	66	13,541	84	11,398	84	11,425
10,000	123	14,718	97	17,463	70	19,085	70	23,707	67	23,640	92	17,850	88	18,055	112	15,197	111	15,233
15,000	184	22,077	146	26,194	105	28,628	105	35,560	73	34,461	137	26,775	131	27,083	168	22,796	167	22,849
20,000	245	29,437	170	40,899	140	44,115	119	46,910	73	43,268	183	35,700	175	36,111	225	30,395	223	30,465
25,000	307	36,796	213	51,124	175	55,144	119	56,511	73	50,414	229	44,625	219	45,138	281	37,994	278	38,082
30,000	368	44,155	256	61,349	210	66,173	119	64,529	73	56,058	275	53,549	240	55,316	337	45,592	334	45,698
40,000	491	58,873	315	94,614	280	100,567	119	76,330	73	63,300	285	78,460	240	88,857	449	60,790	445	60,931
50,000	613	73,592	394	118,268	350	125,708	119	83,149	73	65,814	285	119,127	240	133,007	562	75,987	557	75,164
75,000	920	110,387	563	202,842	526	212,324	119	85,647	73	65,814	285	172,253	240	157,204	619	127,816	573	133,802
100,000	1,227	147,183	751	270,456	701	283,098	119	85,647	73	65,814	285	181,099	240	161,266	619	214,977	573	231,471

Notes:

[1] Payments are calculated using the maximum interest rate for student borrowers, 8.25 percent.

[2] Assumes a 5 percent annual income growth (Census Bureau).

[3] HOH is Head of Household. Assumes a family size of two.

Remember: One can prepay all or part of a student loan at any time without a prepayment penalty.

For more details, see the chart on the previous page, "Examples of Debt Levels, Beginning Monthly Payments, and Total Amounts Repaid for all Direct Loan Repayment Plans."

If a plan is not selected, the Standard Repayment Plan will be assigned. For help deciding which repayment plan to choose, call the Direct Loan Servicing Center at 1-800-848-0979. If none of these plans seems feasible, the Direct Loan Servicing Center will help create a plan that meets a borrower's individual needs.

Changing Repayment Plans

One may experience significant changes in life during the repayment period. The borrower may change or lose jobs, receive salary increases or promotions, or choose to work in a career that provides less income than expected when a repayment plan was selected. The borrower can change repayment plans annually to adjust to these changing circumstances (unless repaying a defaulted loan under the Income Contingent Repayment Plan). There is no limit to the number of times plans can be changed. If repaying under the Income Contingent Repayment Plan, one can choose the 12-year payment limit or remove the limit on the monthly amount once per year.

To change plans, the borrower can

- change to the Income Contingent Repayment Plan at any time. The repayment term will be 25 years, less any time previously spent in the Income Contingent, Standard, and/or Extended (12 year period only) Repayment Plans. Time spent in the Extended Plan under the 15- to 30-year periods and the Graduated Repayment Plan does not count toward the 25-year maximum term;
- change to another plan as long as that plan has a repayment term greater than the amount of time one already has been in repayment. For example, the borrower can change from the Extended Plan to the Standard Plan only if he or she has been in the Extended Plan less than 10 years. If this type of change is made, the remaining repayment term will be determined by subtracting the amount of time already in repayment from the term allowed for the new plan. For example, if the borrower has been on the Extended Plan for three years and then converts to the Standard Plan in order to pay off the loan more quickly and reduce the interest expense, he or she will have a maximum of seven years left to repay the loan.

If repaying a Federal Direct Consolidation Loan (Direct Consolidation Loan) that one agreed to repay under the Income Contingent Repayment Plan due to a previous defaulted loan, the borrower must make six consecutive monthly payments before changing to another plan.

Loan Consolidation

If the borrower has several student loans (including other federal education loans), it may be to his or her advantage to consolidate loans into a single Direct Consolidation Loan. Consolidation means making only a single monthly payment to cover all of one's federal loans.

Because the interest rate will be the same as for Direct Loans, the borrower may also be able to pay less interest than he or she is paying on current loans. The borrower can choose the repayment plan that best suits his or her financial circumstances.

Note: If the borrower wants to consolidate during the grace period, he or she should wait until the last month of the grace period to apply. Repayment on consolidation loans begins within *60 days* of the first loan disbursement, which means the grace period would be cut short if the borrower applied too early.

Once the borrower leaves school, he or she can consolidate an FFEL under Direct Loans only if an FFEL consolidation loan or an FFEL consolidation loan with income-sensitive repayment terms acceptable to him or her cannot be obtained.

Similar conditions apply to parents. They must have an outstanding balance on a Direct PLUS Loan or a Federal PLUS Loan (under the FFEL Program). Parents must not have an adverse credit history or, if they do, must either obtain an endorser for the loan who does not have an adverse credit history, or must document extenuating circumstances.

Even defaulted loans may be consolidated if the borrower agrees either to repay the loan under the Income Contingent Repayment Plan, or the borrower makes satisfactory arrangements to repay the loan (for consolidation purposes, defined as three consecutive, voluntary, on time, full monthly payments).

Note: Married couples may consolidate their loans jointly if at least one spouse meets the requirements for loan consolidation. Both spouses will be responsible for repayment of the loan, even if one spouse dies or they separate or divorce.

Listed below are the types of loans that may be consolidated:

- Direct Stafford/Ford Loans (subsidized and unsubsidized)
- FFEL Stafford Loans (subsidized and unsubsidized)
- Direct and Federal PLUS Loans
- Guaranteed Student Loans (GSL)
- Federal Insured Student Loans (FISL)
- Federal Supplemental Loans for Students (SLS)
- Auxiliary Loans to Assist Students (ALAS)
- Federal Perkins Loans
- National Direct/Defense Student Loans (NDSL)
- Health Professions Student Loans (HPSL)
- Health Education Assistance Loans (HEAL)
- Loans for Disadvantaged Students (LDS)
- Loans made under Subpart II of Part B of Title VIII of the Public Health Service Act, including nursing loans
- Direct and Federal Consolidation Loans

Borrowers can consolidate their loans at any time while they are still in school, during their six-month grace period, or after they begin repayment. If borrowers want to consolidate while they are in school, and they are attending a Direct Loan school, they must have at least one Direct Loan or FFEL that is in an "in-school period." If borrowers are attending a non–Direct Loan school, they must have a Direct Loan in an "in-school period." An "in-school period" begins when the loan is disbursed and ends when the borrower ceases to be enrolled half-time. Borrowers can consolidate only Direct Loans and FFELs while they are in school; the other types of loans listed above may be consolidated after they leave school.

This allows the borrower to extend his or her repayment term, reduce his or her monthly payments, and work with a single lender instead of several different lenders. Last, if the borrower is interested in a Direct Consolidation Loan, contact the Consolidations Department of the Direct Loan Servicing Center at 1-800-557-7392.

Loan Deferments

Once the borrower is no longer enrolled at least half-time in college and a six-month grace period has ended, loan repayment for Federal Direct Stafford Loans may be deferred

- during any period in which one is pursuing at least a half-time course of study as determined by the institution;
- during any period in which the borrower is pursuing a course of study under an approved graduate fellowship program or rehabilitation training program for disabled individuals;
- for up to three years during periods in which one is actively seeking but unable to find full-time employment;
- for up to three years for any reason, which Caltech determines, that has caused or will cause the borrower to have an economic hardship.
- for up to three years during periods in which the borrower who is serving as a member of the Armed Forces is called or ordered to active military service for a period of more than 30 days.

Unlike the Federal Perkins Loan program, which provides for a six-month grace period following each period of statutory deferment, there are no postdeferment grace periods for Federal Direct Stafford Loans.

More specific information of repayment and deferments are included in the loan promissory note and the loan disclosure statement provided to student borrowers.

Financial Payment Plans

Several private organizations offer a variety of financing options (such as monthly payment plans and long-term loans) to assist students and families in meeting college expenses. Information describing these programs is available upon request from the Caltech Financial Aid office and on the Caltech Financial Aid home page at http://www.finaid.caltech.edu/.

Merit Awards

Merit Awards are awarded annually to *returning* students solely on the basis of academic merit. Financial need is not factored in the recommendation process. These Upper Class Merit Awards include the endowed Caltech Prizes, Carnation Scholarships, Rosalind W. Alcott Awards, and several other private and corporate scholarships. The Faculty Committee on Scholarships and Financial Aid recommends a number of Caltech's most academically talented students for receiving merit awards their sophomore, junior, and/or senior year. The John Stauffer Scholarship is also awarded to a student with a chemistry-related major. In 1999–2000, 46 students were awarded Caltech Merit Awards in amounts ranging from $6,425 to $19,260. The honor is recorded on academic transcripts and listed in the commencement bulletin when the scholar graduates.

In addition, the Freshman Admissions Committee selects admitted freshmen for a limited number of merit-based awards. No separate application is required. Selected students will be notified by letter.

Several corporations, including Northrop and Green Hills Computer Software, offer partial- or full-tuition scholarships to students demonstrating particular facility in the options that represent the types of expertise the corporations need in their research and development groups. As these and other organizations announce competitions throughout the year, eligibility criteria and deadlines are advertised by the Financial Aid office in the student newspaper—the *California Tech*—and on the Financial Aid office home page at http://www.finaid.caltech.edu/.

Study Abroad

Caltech may provide 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. Enrollment in a program of study abroad approved for credit by Caltech may 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 Cambridge Scholars Program, 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 Scholars will be provided a Memo of Understanding outlining the terms of their study abroad participation. (For more information on the Caltech Cambridge Scholars Program, see page 122.)

For eligible students wishing to study abroad, the costs will not exceed the prorated costs of attending Caltech for the same academic period. These 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. The eligible student will have his or her expected family contribution and financial package calculated in the same manner as other students. Because students are usually unable to work while out of the country, they will receive a larger loan component as part of their financial aid award to compensate for their inability to work. Students studying abroad are subject to the standard Caltech policy of a maximum of 12 terms of eligibility for financial aid.

Cambridge 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 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 home page. Such scholarships can also often be found with the help of a search service. We recommend fastWEB, SRN, ExPAN, MACH25, CASHE, and Fund Finder. (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. In general, the amount of each outside merit award will be used to replace a like

amount of the self-help (work and/or loan) portion of the financial aid award. If the amount of the outside award exceeds the self-help portion, the excess amount will replace Caltech grant eligibility.

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 on page 167. Whenever this is not maintained, approval for reinstatement by the Undergraduate Academic Standards and Honors Committee, the registrar, or the dean of undergraduate students (as described on pages 125 and 126) 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 of 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 (see page 129) must be approved by the registrar or Undergraduate Academic Standards and Honors Committee. Students enrolled half-time (taking 18 to 26 units) will be expected to work additional hours during the academic year, as well as to accept a reduction in the books and supplies allowance of their college expense budget. All students planning to carry an underload (less than 36 units) should contact the Financial Aid office.

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 $3,000 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.

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.

The 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.

Caltech Prize Scholarships and Carnation Scholarships
Each year Caltech awards these prizes for academic excellence to continuing students. They are based solely on merit (selection is made on the basis of grades, faculty recommendations, and demonstrated research productivity) with no consideration given to need or any other nonacademic criterion.

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 Residence Life and Master's Award
Two awards, selected by the deans, and the director of residence life and the master, 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 division chairs and the deans, together with the Undergraduate Academic Standards and Honors Committee.

George W. Green Memorial Prize
The George W. 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 division chairs and the deans, together with the Undergraduate Academic Standards and Honors Committee.

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. The award, presented at commencement, consists of a cash award and a certificate.

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.

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 astronomy will annually award the Margie Lauritsen Leighton Prize to one or two undergraduate women who are majoring in physics, astrophysics, or astronomy, and who have demonstrated academic excellence. The prize consists of a cash award and will be made at the end of the sophomore year.

Dorothy B. and Harrison C. Lingle Scholarship
Each year, the Freshman Admissions Committee selects one incoming freshman for a $7,500 annual merit award. 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.

Artur Mager Prize in Engineering
The Aerospace Corporation established the Artur Mager prize to honor Dr. Artur Mager, an alumnus of the California Institute of Technology and formerly group vice president, engineering, of the Aerospace Corporation. Dr. Mager demonstrated outstanding qualities of technical creativity, leadership, and character throughout his career. The prize is awarded to a senior student in engineering selected by the chair of the Division of Engineering and Applied Science based on excellence in scholarship and the promise of an outstanding professional career. The prize consists of a cash award and a certificate.

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.

Millikan Scholarships
Millikan Scholarships are awarded to selected freshmen whose record of personal and academic accomplishment is judged outstanding among the remarkable group of incoming freshmen.

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.

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. 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.

Sigma Xi Award
In accordance with the aim of Sigma Xi, the Scientific Research Society, to encourage original investigation in pure and applied science, the Institute chapter of the society annually awards a prize of $1,200, funded from membership dues, to a senior selected for an outstanding piece of original scientific research. The student is selected by the division chairs and the deans, together with the Undergraduate Academic Standards and Honors Committee.

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." The awardee is chosen by a faculty committee from the Division of the Humanities and Social Sciences.

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.

GRADUATION REQUIREMENTS, ALL OPTIONS

To qualify for a Bachelor of Science degree at the Institute, a student 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. The student must also register for programs that make normal progress toward a B.S. degree.

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 at the proper time, 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

The following requirements are applicable to incoming freshmen for 2000–2001 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[1])	18
3. Freshman Physics (Ph 1 abc)	27
4. Sophomore Physics (Ph 2 ab[2] or Ph 12 abc)	18
5. Freshman Chemistry (Ch 1 ab)[3]	15
6. Freshman Biology (Bi 1)[4]	9
7. Menu Class (currently Ay 1 or Ge 1)	9
8. Freshman Chemistry Laboratory (Ch 3 a)[5]	6
9. Additional Introductory Laboratory	6
10. Science Communication Requirement (Core 1 ab)[6]	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 who entered in 1995–96 or earlier must have previously taken Ma 2 c or else one term from the following: Ma 112 abc, Ma 144 ab, ACM 153 abc.*

[2] *Ph 2 c no longer exists. Students who have taken part but not all of Ph 2 in 1995–96 or earlier must take a set of courses that covers at least the material in the current Ph 2. One term from the following courses may be substituted for Ph 2 c: Ph 12 c, APh 17 c, Ch 21 c, Ch 24 a.*

[3] *Ch 1 c no longer exists. Students who entered in 1995–96 or earlier who have not taken Ch 1 c should take Bi 1 or an acceptable replacement to Ch 1 c as follows: The Chemistry requirement can also be met by completing two terms of Ch 41 abc or Ch 21 abc. Ch 10 c can be taken in place of Ch 1 c.*

[4] *Bi 8 and Bi 9, if taken in the freshman year, are an acceptable alternative to Bi 1.*

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

[6] *This requirement is to be met in the junior year.*

Undergraduate Probability Requirement

All students are required to demonstrate a knowledge of basic probability. They can demonstrate this in one of four ways: (1) The most common way will be that students who take the regular Ma 1 a will have five weeks of probability as part of Ma 1 a and by passing Ma 1 a will have met the requirement. (2) Students who receive advanced placement for Ma 1 as part of the advanced placement exams may satisfy the probability requirement by taking and passing a subsequent probability exam. (3) By passing a special seven-week course, Ma 1 d, in the third quarter of their freshman year. (4) Students who otherwise place out of all of Ma 1 or others with special circumstances may demonstrate their knowledge of probability by passing a Ma 1 d equivalency exam, subject to the approval of the executive officer for mathematics.

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) shall be taken during the freshman year. The additional 6 units must be chosen from one of the following: APh 9 (6 units), APh 24 (6 units), Bi 10 (6 units), Ch 3 b (6 units), Ch 4 ab (6 units per term), ChE 10 (6 units), EE 4 (3 units), E 5 (6 units), Ph 3 (6 units), Ph 5 (6 units), or a more advanced laboratory. Computational laboratory courses may not be used to satisfy this requirement.

Science Communication Requirement

See Core, page 384.

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; history; humanities; literature; music; philosophy; science, ethics, and society; and, with certain restrictions, languages) and 36 in the social sciences (anthropology, economics, law, political science, psychology, social science), in each case divided equally between introductory and advanced courses. The remaining 36 may be drawn from humanities and social sciences,

including HSS Tutorial courses and (to the limit of 27 units) courses in business economics and management. They may *not* include reading courses unless credit has been granted by petition to the Humanities or Social Science faculty. With the exception of SES 10 ab, 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," humanities courses numbered 10 or below in the *Catalog*. These classes introduce students to the basic issues in the three core disciplines of history, literature, and philosophy, and successful completion of two terms of freshman humanities is a prerequisite for all advanced 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.

A student must take 18 units of advanced humanities courses as well. The classes that count as advanced humanities courses are those numbered 99 or above in art history; history; humanities; literature; music; philosophy; and science, ethics, and society. The advanced humanities classes also include all foreign language classes beyond the fourth term. The first four terms of a foreign language 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.

To encourage breadth, students will have to take their two freshman humanities classes in different disciplines, the disciplines for the freshman classes being history, literature, and philosophy. When they take their two required advanced courses, students will have to choose at least one class from a third discipline. For the advanced courses, the disciplines will include not only history, literature, and philosophy, but also art history, music history, and languages beyond the fourth term. If a student meets his or her freshman humanities requirement by taking SES 10 ab, which mixes history and philosophy of science, then he or she must meet the advanced breadth requirement by taking a class outside of SES, and outside of history and philsophy as well; otherwise, he or she would be leaving Caltech with no contact whatsoever with art, languages, or literature.

Since writing is important, all humanities courses, with the exception of foreign languages, will require at least 4,000 words of composition. The instructors will give extensive feedback on written work and will help students improve their prose. In addition, all freshmen will take a writing examination administered at Caltech before the beginning of the fall term. Freshmen who fail this examination may not enter freshman humanities classes until they successfully complete En 1 ab, English as a Second Language, or En 2, Basic English Composition. These courses count as general Institute credit only. Finally, all students will have to satisfy a

writing proficiency requirement in both of their freshman humanities classes. If a student fails to meet this requirement in either class, he or she will have to pass En 1 ab, En 2, or another suitable composition course before taking further freshman or advanced humanities.

Students are required to take 18 units of introductory social science courses, consisting of two courses of 9 units each, chosen from anthropology: An 22; economics: Ec 11; law: Law 33; political science: PS 12; psychology: Psy 15; or social science: SS 13.

Students must also take 18 units of courses numbered 100 or above, selected from the following categories: anthropology, economics, law, political science, psychology, and social science, but only from a field in which they have completed an introductory course. All 18 units of advanced social science credit can be taken from the same area as long as the appropriate introductory course has been taken.

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 (4-0-5)	9		9		9
Ph 1 abc	Classical Mechanics and Electromagnetism (4-0-5)	9		9		9
Ch 1 ab	General and Quantitative Chemistry (3-0-3 for Ch 1 a; 4-0-5 for Ch 1 b)	6		9		0
Bi 1	Fundamentals of Modern Biology	0		0		9
Ch 3 a	Experimental Chemical Science (0-6-0)[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[4]	x		x		x
PE	Physical Education[5]	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 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 9 (6 units), Bi 10 (6 units), Ch 3 b (6 units), Ch 4 ab (6 units per term), E 5 (6 units), Ph 3 (6 units), Ph 4 (6 units), or a more advanced laboratory course.*

[3] *Students entering 1996-97 or later years must take a menu course (currently Ay 1 or Ge 1) 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] *A partial list of electives particularly recommended for freshmen includes the following: Ay 1, Bi 8, ChE 10, Ch 10, CS 1, CS 2, CS 3, EE 1, Env 1, Ge 1, Ph 10, Ph 20, Ph 21, Ph 22.*

[5] *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.*

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. 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, ACM 95 abc, ACM 101, ACM 102 a, ACM 102 b, and E 10.
2. An approved sequence of three one-quarter courses to be selected from the following: ACM 101, ACM 102 a, ACM 102 b, ACM 103, ACM 104, ACM 110, ACM 111, ACM 112, ACM 113.
3. One of the following (or an approved combination): Ma 108abc, Ma 109 abc, Ma 110 abc, Ma 120 abc, Ma 121 abc, Ma 122 a, EE/Ma 126 ab, EE/Ma 127 ab, CS/EE/Ma 129 abc, Ma 151abc.
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 483 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	0
Ph 2 ab	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	0
Ma 5 abc	Introduction to Abstract Algebra (3-0-6)	9	9	9
	Humanities Electives	9	9	9
	Electives	9	9	27
		45	45	45
Third Year				
ACM 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives	9	9	9
	Electives	18	18	18
		39	39	39

Fourth Year				
ACM 101	Ordinary Differential Equations (3-0-6)	9	0	0
ACM 102 ab	Partial Differential Equations (3-0-6)	0	9	9
	Humanities Electives	9	9	9
	Electives[1]	27	27	27
		45	45	45

[1] *See items 2 and 3 under option requirements.*

Applied Physics Option

The applied physics option is designed to connect what are conventionally considered "engineering" and "pure physics." Research in applied physics is an effort to answer questions related to problems of technological concern. Since the interests of both engineering and pure physics cover fields that overlap, a definite dividing line cannot be drawn between them. Realizing this, 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. This interdivisional aspect of the 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 different fields of technology. Solid-state physics includes work in superconductivity, amorphous solids, and semiconducting solid states. Work on electromagnetic waves extends from antenna problems into lasers and nonlinear optics. Fluid physics includes magnetohydrodynamics, high-temperature plasmas, and superfluids. Transport phenomena in gases, liquids, and solids form another active area related to nuclear and chemical engineering.

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.

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 subjects listed below under option requirements may be refused permission to continue work in this option.

Option Requirements

1. Any three of the following: APh 9 b, APh 24, Ph 3, Ph 5, Ph 6, Ph 7.
2. APh 17 abc, APh 25, APh 125 ab or Ph 98 ab, and Ph 106 abc.
3. ACM 95 abc.
4. Either APh 78 abc or one term of APh 77 and one chosen from the following: APh 77, Ph 77, EE 91, Ch 6, Ae/APh 104 bc, MS 125, APh 124.

5. 27 additional units of APh courses numbered over 100, which must include one of the following sequences: APh 101 abc, APh 105 abc, APh 114 abc, APh/MS 141 bc, APh 156 abc, APh/EE 183 ab, APh 190 abc, or the sequence APh/EE 130 abc. Note that APh 100 and APh 200 do not satisfy this requirement.
6. Passing grades must be earned in a total of 486 units, including the courses listed above. None of the courses taken to satisfy option requirements may be taken on a pass/fail basis.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 2 ab	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	0
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	0
	Humanities Electives	9	9	9
	Laboratory Electives[1]	6	6	6
APh 17 abc	Thermodynamics (3-0-6)	9	9	9
APh 25	Introductory Quantum Mechanics	-	-	9
	Other Electives	9	9	18
		51	51	51
Third Year				
Ph 98 ab	Quantum Mechanics	9	9	-
APh 110 abc	Topics in Applied Physics	2	2	2
ACM 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives	9	9	9
	Other Electives[2]	18	18	27
		50	50	50
Fourth Year				
APh 78 abc or	Senior Thesis, Experimental[3]	6	6	6
APh 77	Laboratory in Applied Physics[3]	9	9	-
APh 106 abc or				
Ph 106 abc	Topics in Classical Physics	9	9	9
APh	Electives[2]	9	9	9
	Humanities Electives	9	9	9
	Other Electives	18	18	18
		51-54	51-54	51

[1] *See item 1, option requirements.*
[2] *See item 5, option requirements.*
[3] *See item 4, option requirements.*

Suggested Electives

The student may elect any course that is offered in any term provided he or she has the necessary prerequisites for that course. The following subjects are especially suitable for a well-rounded course of study. They need not be taken in the year suggested.

Second Year	*Third Year*	*Fourth Year*
APh 23, APh 24, Ge 1, Bi 7, Ay 1, EE 14 abc, Ma 5 abc, MS 15 abc	APh 77, Ph 77 ab, EE 114 abc, Ch 6 ab, Ge 101, APh 100, ME 19 abc	APh 77, APh 100, Ae/APh 101 abc, APh 105 abc, APh 114 abc, ACM 105 ab, ACM 101 abc, ACM 104, Ch 125 abc, Ph 125 abc, Ph 129 abc, Ph 77 ab

More Specialized Courses
APh 156 abc, APh 183 ab, APh 190 abc, APh/EE 130, AM 135 abc, ChE 103 abc, EE 91 abc, Ge 102, Ge 103

Astronomy Option

The astronomy option is designed to give the student an understanding of the basic facts and concepts of astronomy, to stimulate his or her interest in research, and to provide a basis for graduate work in astronomy. The sophomore-junior sequence (Ay 20, 21, 101, 102) constitutes a solid introduction to modern astronomy. More advanced courses may be taken in the junior and senior years.

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, Ay 21 or 102, Ay 30 or Ay 141, Ay 101, 14 units of Ay electives (excluding Ay 1), Ph 3, Ph 5 or 6, Ph 7, Ph 98 abc or Ph 125 abc or APh 125 abc, and Ph 106 abc.
2. 54 additional units of Ay or Ph courses.
3. 27 additional units of science or engineering electives, of which 18 must be outside the Division of Physics, Mathematics and Astronomy.
4. 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	Waves, Quantum Mechanics, and			
or	Statistical Physics (4-0-5)	9	9	-
Ph 12 abc[1]	Quantum and Statistical Mechanics (3-0-6)			
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ay 20	Basic Astronomy and the Galaxy (3-0-6)	9	-	-
Ay 21	Galaxies and Cosmology (3-0-6)	-	-	9
Ay 30	Current Trends in Astronomy (2-0-1)	-	3	-
Ph 3, 5, 6, 7	Physics Laboratory[2]	0-6	6	0-6
	Core Menu Course	-	-	9
	Humanities Electives	9	9	9
	Electives[3]	0-9	3-6	12-15
	Suggested total number of units	36-51	39-42	39-48
Third Year				
Ph 98 abc	Quantum Physics (3-0-6)	9	9	9
Ph 106 abc	Topics in Classical Physics (3-0-6)	9	9	9
Ay 101	The Physics of Stars (3-2-6)	-	11	-
Ay 102	Plasma Astrophysics and the Interstellar Medium (3-0-6)	-	-	9
	Humanities Electives	9	9	9
	Electives	18-24	9-12	9-15
	Suggested total number of units	45-51	47-50	45-51
Fourth Year				
	Astronomy or Physics Electives	18	18	18
	Humanities Electives	9	9	9
	Electives	18-24	18-24	18-24
	Suggested total number of units	45-51	45-51	45-51

An ability to verbally 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. Students are encouraged (but not required) to undertake research leading to a senior thesis; credit for this work is provided through Ay 42.

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[4], APh 23/24, Ay 105, Ay 121[4], Ay 122, Ay 123, Ay 124, Ay 125, Ay 126, Ay 127, Ay 145, EE 20, EE 91, EE 157, Ge 1, Ge/Ay 11 c, Ge 103, Ge 131, Ge/Ay 132[4], Ge 153, Ge 167, Ma 5, Ma 112, Ph 77, Ph 125[4], Ph 129, Ph 136[4], Ph 236.

[1] *Prerequisite for Ph 98.*

[2] *Students are required to take (a) Ph 3 if not already taken, (b) Ph 5 or Ph 6, and (c) Ph 7.*

[3] *Sophomore electives include at least 27 units of science and engineering courses, of which at least 18 units must be in subjects other than mathematics, physics, and astronomy. It is desirable for a student to acquire as broad a background as possible in other related fields of science and engineering.*

[4] *Students who plan to do graduate work in astronomy should elect some of these courses during their third and fourth years, in consultation with their advisers.*

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, Sally J. Asmundson, at the Career Development Center.

Option Requirements

1. Bi 8, Bi 9, Bi 11 or Bi 12, Bi/Ch 110, Bi 122, Bi 150, and Ch 41 abc.
2. One advanced laboratory course chosen from Bi 123, Bi 161, Bi 162, or Bi 180.
3. Three courses chosen from Bi/Ch 111, Bi/Ch 113, Bi 114, Bi/Ch 132, Bi 156, BMB/Bi/Ch 170, Bi 188, Bi 189, or Bi 190. Only one of the three may be a six-unit course (these are 188, 189, and 190).
4. 3 units of Biology Major Seminar, Bi 80.
5. 34–49 elective units in Biology courses numbered above 20, to reach a total of 143 units of Biology course work. Pass/fail grading may be elected, in the manner specified on page 42, for these Biology course electives, but not for courses taken to fulfill requirements (1) to (4).
6. Passing grades must be earned in a total of 486 units, including the courses listed above.

Recommended Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
	HSS Electives	9	9	9
Ma 2 ab	Linear Algebra, Statistics, and Differential Equations (4-0-5)	9	9	-
Ph 2 ab	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	-
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
Bi 8	Introduction to Molecular Biology (3-0-6)	-	9	-
Bi 9	Cell Biology (3-0-6)	-	-	9
Bi 10	Cell Biology Laboratory [1] (1-3-2)	-	-	6
	Electives[2]	9-15	0-6	9-18
		45-51	45-51	42-51

Third Year				
	HSS Electives	9	9	9
Bi 12	Introduction to Developmental Biology (3-0-6)	-	-	9
Bi/Ch 110	Biochemistry (4-0-8)	12	-	-
Bi 122	Genetics (3-0-6)	9	-	-
Bi 123	Genetics Laboratory[3]	-	9	-
Ch 21 a	The Physical Description of Chemical Systems[4] (3-0-6)	9	-	-
Ch 24 ab	Introduction to Biophysical Chemistry[4] (3-0-6)	-	9	9
	Electives [5,6]	6-12	18-24	27-33
		45-51	45-51	54-60
Fourth Year				
	HSS Electives	9	9	9
Bi 80	Biology Major Seminar	3	-	-
Bi 150	Neurobiology (4-0-6)	10	-	-
	Electives[5,6]	23-26	36-42	36-42
		45-48	45-51	45-51

Suggested Electives

Second Year: Bi 23, Ch 4 ab.

Third Year: Bi 22, Bi 23, Bi/Ch 111, Bi/Ch 113, Bi 114, Bi 115, Bi 123, Bi 137, Bi 152, Bi 156, Bi 157, Bi 158, Bi 161, Bi 162, Ch 7.

Fourth Year (in addition to those listed for the third year): Bi 90, Bi 125, Bi 127, Bi/Ch 132, Bi 170, Bi 180, Bi 188, Bi 189, Bi 190, Bi 217, Bi 218, Bi 219, Bi 220, Ch 145, Ch 146, CNS/Bi 186.

[1] *Bi 10 is not required for the biology option but is commonly taken by biology students to meet the Institute Introductory Laboratory requirement.*

[2] *Second-year electives should include an Institute Core Elective, if this requirement was not met during the first year.*

[3] *Recommended for students planning to take any additional courses in genetics.*

[4] *The combination of Ch 21 a and Ch 24 ab, or Ch 21 abc, 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.*

[5] *Electives must include courses to satisfy option requirements (2) and (3), and sufficient additional units of work in biology to satisfy the total of 143 units as specified by requirement (5). Note that Bi 1, Bi 2, and Bi 10 are not counted toward this total.*

[6] *The sequence of courses Bi 150, Bi 152, Bi 156, and Bi 157 is intended to provide a comprehensive introduction to the field of neurobiology.*

Chemical Engineering Option

Aims and Scope of Undergraduate Study in Chemical Engineering

The chemical engineering option is designed to prepare its students for either graduate study, or research and development work in industry. It accomplishes this by building on the core curriculum to provide a broad and rigorous exposure to the fundamentals of chemical engineering while maintaining a balance between classroom lectures and laboratory and design experience. 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.

Chemical engineering involves applications of chemistry, physics, mathematics, and, increasingly, biology and biochemistry. In addition to basic physics, chemistry, and mathematics, 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, separations, and the integrating subjects of process 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 the metallurgical industries; or in the biotechnology industry. Chemical engineering underlies most of the energy field, including the efficient production and utilization of coal, petroleum, natural gas, and in newer technologies like fuel cells. Air and water pollution control and abatement 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.

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 also take the second-year 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 or CS 2).

Undergraduate research is emphasized, and students are encouraged, even in the freshman year, to participate in research with the faculty. An optional senior thesis is a unique aspect of the chemical engineering program.

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

ac, ChE 103 abc, ChE 104, ChE 105, ChE 110 ab[1], ChE 126 a[1], ChE 126 b[1] or ChE 90 ab, ChE 152, and either Ec 11, BEM 101, or BEM 103[2].
2. 9 units of chemistry electives.
3. 33 units of engineering electives[3].
4. Passing grades must be earned in all courses required by the Institute and the option.

[1] *Two terms of either ChE 126 ab or ChE 110 ab fulfills the science communication requirement.*
[2] *These 9 units partially satisfy the Institute requirements in humanities and social sciences.*
[3] *These electives may include up to 18 units of ChE 80.*

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ph 2 ab	Sophomore Physics (4-0-5)	9	9	-
Ch 3 b	Experimental Procedures of Synthetic Chemistry (1-6-1)	8	-	-
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
ChE 63 ab	Chemical Engineering Thermodynamics (3-0-6)	9	9	-
ChE 64	Principles of Chemical Engineering (3-0-6)	-	-	9
	Introductory "menu" course from a specified list (3-0-6) or Elective	-	-	9
	Electives	-	9	9
		44	45	36
Third Year				
ACM 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
Ch 21 ac	The Physical Description of Chemical Systems (3-0-6)	9	-	9
ChE 103 abc	Transport Phenomena (3-0-6)	9	9	9
	Electives	18	18	18
		48	39	48
Fourth Year				
ChE 90 ab	Senior Thesis (0-4-5)	-	9	9
ChE 104	Separation Processes (3-0-6)	9	-	-
ChE 105	Process Control (3-0-6)	9	-	-
ChE 110 ab	Optimal Design of Chemical Systems (3-0-6)	-	9	9
ChE 126 ab	Chemical Engineering Laboratory (1-6-2)	9	9	-
ChE 152	Heterogeneous Kinetics and Reaction Engineering (3-0-6)	9	-	-
	Electives	15	18	18
		51	45	

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. Students who show themselves to be qualified and receive the instructor's consent may elect to take an Advanced Placement chemistry course (at least two terms from Ch 21 abc or Ch 41 abc). 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.

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 Undergraduate Study Committee.

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 abc, and Ch 41 abc. Within the total period of undergraduate study there are additional Institute requirements for Ma 1 abc, Ph 1 abc, Ma 2 ab, Ph 2 ab, and 108 units of humanities and/or social science as well as 9 units of PE.

Double Majors

For students simultaneously pursuing a degree in a second option, courses taken as *required* courses for that option can also be counted as chemistry electives (requirement 3, below) where appropriate. However, courses that count toward the electives requirement in the other option cannot simultaneously be counted toward satisfying the elective requirement in chemistry.

The courses listed below would constitute a common core for many students in the option.

Any student of the chemistry option whose grade-point average is less than 1.9 will be admitted to the option for the following

year only with the special permission of the Division of Chemistry and Chemical Engineering.

Option Requirements

1. Ch 14, Ch 21 abc (or Ch 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 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 ab, and ChE/Ch 164, but excluding Ch 180, Ch 280, and Bi/Ch 202.
4. Passing grades must be earned in the courses that constitute the approved program of study, including those listed above.
5. Passing grades must be earned in a total of 486 units, including courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ph 2 ab	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	-
Ch 4 ab	Synthesis and Analysis of Organic and Inorganic Compounds	-	9	-
Ch 5 a	Advanced Techniques of Synthesis and Analysis (1-6-2)	9	-	9
	Electives	6-9	6-9	33–36
PE	Physical Education (0-3-0)	3	3	3
		45-48	45-48	54-57
Third Year				
Ch 14	Chemical Equilibrium and Analysis (2-0-4)	6	-	-
Ch 15	Chemical Equilibrium and Analysis Laboratory (0-6-4)	10	-	-
Ch 21 abc	The Physical Description of Chemical Systems (3-0-6)	9	9	9
Ch 90	Oral Presentation (1-0-1)	-	2	-
	Electives	18-22	36-40	36-40
		43-47	47-51	45-49
Fourth Year				
Ch 6 a	Application of Physical Methods to Chemical Problems (0-6-4)	-	10	-
	Electives	47-51	37-41	47-51
		47-51	47-51	47-51

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[1,2]

	Second Year	*Third Year*	*Fourth Year*
Inorganic Chemistry	Ch 4 ab, Ch 5 a, Ch 41abc, Ma 2 ab, Ph 2 ab, HSS elective, other elective	Ch 5 b[3], Ch 14, Ch 21 abc, Ch elective(s)[4], Ch laboratory[5], Ch 80[6], Ch 90, HSS elective	Ch 6 a or 6 b, Ch electives[4,5], Ch 80[6], HSS elective
Chemical Physics	Ch 4 ab, Ch 21 abc[7], Ch 6 ab[7], Ch 14, Ma 2 ab, Ph 2 ab, HSS elective	Ch laboratory[8], Ch 41 abc[7], Ch elective(s)[9], Ch 80[6], Ch 90, HSS elective, ACM 95 abc	Ch 125 abc, Ch electives[8,9], Ch 80[6], HSS elective
Organic Chemistry	Ch 4 ab[3], Ch 5 a, Ch 41abc, Ma 2 ab, Ph 2 ab, HSS elective, other elective	Ch 5 b or Ch 7, Ch 14, Ch 21 abc, Ch elective(s)[10], Ch laboratory[5], Ch 80[6], Ch 90, HSS elective	Ch 6 a or Ch 6 b, Ch electives[5,10], Ch 80[6], HSS elective
Biochemistry	Ch 4 ab, Ch 5 a or Bi 10, Ch 41 abc, Bi 1, Bi 9, Ma 2 ab, Ph 2 ab, HSS elective	Ch laboratory[11], Ch 7, Ch 14, Ch 21 a, Ch 24 ab (or Ch 21 bc), Ch 80[6] (or Bi 22), Ch 90, Bi/Ch 110, Bi/Ch 111, Bi/Ch 113, Bi 10, HSS elective	Ch 6 a or 6 b, Ch (Bi) electives[11, 12], Ch 80[6] (or Bi 22), HSS elective

[1] *A significant fraction of the chemical literature, especially in organic chemistry, is in German. A reading knowledge of German is therefore useful in research at the doctoral level. Russian is another important language for chemistry; however, the leading Russian periodicals are translated and published in English.*

[2] *Experience in computer programming and use is now important to all areas of chemistry.*

[3] *Requires Ch 4 ab.*

[4] *Ch 112, Ch 117, Ch 120 ab, Ch 121 ab, Ch 122 abc, Ch 135 ab, Ch/ChE 140, Ch 143, Ch 144 ab, Ch/ChE 147, Ch 154, ChE/Ch 155, Env/Ch/Ge 175 abc, Ch 212 ab, Ch 213 abc, Ch 221.*

[5] *Ch 6 ab, Ch 7, Ch 15, Ch 118 ab, Bi 10.*

[6] *See "Research Opportunities for Undergraduates in Chemistry," which may be obtained from the Chair of the Undergraduate Studies Committee. No more than 27 units of Ch 80 will count toward the 486-unit graduation requirement without a senior thesis.*

[7] *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.*

[8] *Ch 5 ab, Ch 15, Ch 118 ab, Bi 10.*

[9] *Ch 120 ab, Ch 121 ab, Ch 126, Ge/Ch 128, Ch 130, Ch 135 ab, Ch/ChE 140, Ch 144 ab, Ch/ChE 147, ChE/Ch 148, ChE/Ch 164, ChE/Ch 165, Ch 221, Ch 224, Ch 227 ab, Ph 106 abc,* ACM *105 ab.*

[10] *Ch 112, Ch 120 ab, Ch 121 ab, Ch 122 abc, Ch 135 ab, Ch 143, Ch 144 ab, Ch 145, Ch 146, Ch/ChE 147, Ch 154, ChE/Ch 155, Env/Ch/Ge 175 abc, Ch 242 ab, Ch 247.*

[11] *Ch 5 b, Ch 15, Ch 6 ab, Ch 7, Ch 118 ab.*

[12] *Ch 122 ab, Bi/Ch 132 ab, Ch 143, Ch 144 ab, Ch 145, Ch 146, Ch 154, Bi/Ch 170, Ch/Bi 231, Ch 242 ab, Ch 244 ,Ch 247.*

Suggested Elective Courses for the Chemistry Option

1. *Chemical Engineering:* Introduction to Chemical Engineering Systems (ChE 10), Chemical Engineering Thermodynamics (ChE 63), Undergraduate Research (ChE 80), Chemical Reaction Engineering (ChE 101), Transport Phenomena (ChE 103), Separation Processes (ChE 104), Physical and Chemical Rate Processes (ChE 151), Special Topics in Transport Phenomena (ChE 174), Protein Technology (ChE 177).
2. *Biology:* Introduction to Molecular Biology (Bi 7), Cell Biology (Bi 9), Genetics (Bi 122), Immunology: Signaling, Gene Regulation, and Development (Bi 114), Multicellular Assemblies (Bi 137), Molecular Neurobiology (Bi 156), Methods in Molecular Genetics (Bi 180).
3. *Engineering:* Introductory Methods of Applied Mathematics (ACM 95), Laboratory Research Methods in Engineering and Applied Science (E 5), Solid-State Electronics for Integrated Circuits (APh 9), Introduction to Sequential Programming (CS 1), Problem Solving and Computing Lab (CS 2).
4. *Physics:* Physics Laboratory (Ph 3, Ph 4, Ph 5, Ph 6, Ph 7), Topics in Classical Physics (Ph 106), Quantum Mechanics (Ph 125), Mathematical Models of Physics (Ph 129), Statistical Physics (Ph 127).
5. *Humanities:* Introduction to Economics (Ec 11), Elementary French (L 102) or Elementary German (L 130) or Elementary Russian (L 141).
6. *Miscellaneous:* Introduction to Astronomy (Ay 1), Engineering Problems of the Environment (Env 1), Principles of Materials (MS 15), Introduction to Earth and Planetary Sciences (Ge 1), Introduction to Isotope Geochemistry (Ge 140), Classical Analysis (Ma 108).

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 or law and economics.

The option is sufficiently flexible that students can combine their pursuit of economics with studies in other areas, such as engineering, physics, or mathematics. The core of the option consists of Introduction to Economics, Ec 11; Theory of Value, Ec 121; and Econometrics, Ec 122. Students are strongly encouraged to supplement this core with additional electives in economics, political science, and mathematics.

Option Requirements

1. Ec 11, Ec 121 ab, and Ec 122, Ec/SS 20.
2. Ma 112 a.
3. Ec 161 or Ec 162.
4. Ec 105 or Ec 145.
5. 54 additional units of advanced economics and social science courses. (Courses that are used to fulfill the Institute upperclass social science requirement [courses numbered 100 and above] will also count toward the 54 additional units required under the economic and social science options.) Students may take any or all of ACM 181 ab, BEM 104, or BEM 105 (or BEM 110 with the consent of the option) in partial fulfillment of this requirement.
6. 45 additional units of science, mathematics, and engineering courses. The requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by any course with a number less than 10.
7. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ph 2 ab	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	-
	Menu Course	-	-	9
Ec 11	Introduction to Economics (3-0-6)	9	-	-
PS 12	Introduction to Political Science (3-0-6)	-	-	9
	Electives[1]	18	27	27
		45	45	45

Third Year				
Ec 105	Industrial Organization (3-0-6)	9	-	-
Ec 121 ab	Theory of Value (3-0-6)	9	9	-
Ec 122	Econometrics (3-0-6)	-	9	-
Ec 162	Monetary Theory (3-0-6)	-	-	9
Ma 112 a	Statistics (3-0-6)	9	-	-
	Electives[1]	27	27	27
		54	45	36
Fourth Year				
	Electives[1]	45	45	45

[1] *See requirements 6 and 7 above.*

Electrical and Computer Engineering Option

Modern technology increasingly combines communications, whether by optical fiber or wireless, and computing in all its forms. Communications is traditionally an area of electrical engineering, and computing is the domain of computer science. The undergraduate option in electrical and computer engineering is offered jointly by the electrical engineering and the computers cience faculties. It provides an intellectual foundation in both computer science and electrical engineering.

The option begins with CS 20 abc and EE 20 ab in the sophomore year. CS 20 is an introduction to computer science. EE 20 is an introduction to electrical engineering, with an emphasis on communication electronics and laboratory work. CS 20 and EE 20 are prerequisites for the junior classes. In the junior year, the students take CS 138 abc, Algorithms, which discusses the design of algorithms in many areas of computer science and provides a strong foundation for advanced courses. In addition, students take EE 32 ab, Signals, Systems, and Transforms, which provides an introduction to Fourier, Laplace, and Z transforms, as well as signals, modulation, sampling, and noise. In their senior year, students undertake a project or a thesis, and electives.

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 in the option requirements may be refused permission to continue work in this option.

Option Requirements

1. E 10.
2. ACM 95 abc.
3. CS 20 abc, EE 20 ab.
4. CS 138 abc, EE 32 ab.
5. CS 141 abc, or CS/EE 181 abc, or EE/CS 80 abc, or 27 units selected from EE/CS 51, EE/CS 52, EE/CS 53, EE 55, EE 90, and EE 91.

6. In addition to the above courses, 27 units of CS or EE courses numbered 100 or over.
7. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ph 2 ab	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	-
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
	Humanities Electives[1]	9	9	9
CS 20 abc	Computation, Computers, and Programs (3-3-3)	9	9	9
EE 20 ab	Electronics Laboratory (3-3-3)	9	9	-
	Electives	-	-	18
		45	45	36
Third Year				
ACM 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives[1]	9	9	9
CS 138 abc	Computer Algorithms (3-0-6)	9	9	9
EE 32 ab	Signals, Systems, and Transforms (3-0-6)	9	9	-
	Electives	-	-	9
		39	39	39
Fourth Year				
	Humanities Electives[1]	9	9	9
E 10	Technical Seminar Presentations (1-0-2)	-	3	-
	Projects[2]	9	9	9
	Technical Electives[3]	9	9	9
	Electives	18	18	18
		45	48	45

[1] *See Institute requirements regarding humanities electives.*
[2] *See option requirement 5.*
[3] *See option requirement 6.*

Electrical Engineering Option

The electrical engineering option is designed to prepare its students for either graduate study or research and development work in government or industrial laboratories. It accomplishes this by building on the core curriculum to provide a broad and rigorous exposure to the fundamentals of electrical engineering. It strives to maintain 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, professional ethics, and an appreciation of the importance of continuing intellectual growth.

Students electing this option will normally choose to take APh 9, solid-state electronics for integrated circuits, as a freshman-year elective. Then in the sophomore year, the formal study of electrical engineering will begin with the theory and laboratory practice of analog and digital electronics, EE 20 ab and EE/CS 51/52, respectively. The junior year features a basic course in linear systems and signal processing, EE 32 ab; an introduction to sensors and actuators, EE 40; an introduction to analog and digital communications, EE 160; and an analog electronics laboratory, EE 90. In the senior year, the student will take electromagnetic engineering, EE 151; and will also be asked to demonstrate his or her ability to formulate and carry out an independent research or design project through either a senior thesis, EE 80 abc, or the senior project design laboratory, EE 91 ab. 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, below.)

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. E 10.
2. ACM 95 abc.
3. EE 20 ab, EE 32 ab, EE 40, EE 151, EE 160.
4. EE/CS 51, EE/CS 52, EE 90.
5. EE 80 abc, or two courses selected from EE 91 ab and EE/CS 53.
6. APh 9 ab.
7. In addition to the above courses, 27 units selected from any EE course numbered over 100, or any multilisted courses numbered over 100 that include EE in the listing. Also, CDS 111, CDS 112, and CDS 113 ab are acceptable.
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	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	-
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
	Humanities Electives[2]	9	9	9
EE 20 ab	Electronics Laboratory (3-3-3)	9	9	-
EE/CS 51	Principles of Microprocessor Systems (3-0-6)	-	9	-
EE/CS 52	Microprocessor Systems Laboratory (1-11-0)	-	-	12
	Electives	-	-	24
		36	45	45
Third Year				
ACM 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives[2]	9	9	9
EE 32 ab	Signals, Systems, and Transforms (3-0-6)	9	9	-
EE 40	Introduction to Sensors and Actuators (3-0-6)	9	-	-
EE 90	Experimental Projects in Analog Circuits	-	-	9
EE 160	Communication System Fundamentals (3-0-6)	-	-	9
	Electives	9	9	9
		48	39	48
Fourth Year				
	Humanities Electives[2]	9	9	9
E 10	Technical Seminar Presentations (1-0-2)	-	3	-
EE 91 ab[3]	Experimental Projects in Electronic Circuits	12	12	-
EE 151	Electromagnetic Engineering (3-2-7)	-	-	12
	Electives	18	18	24
		39	42	45

[1] *A student who follows this "typical schedule" exactly, and who takes APh 9 ab as a freshman, will have taken about 540 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.*

[3] *See option requirement 5.*

Suggested Electives

First-year students interested in electrical engineering should consider taking APh 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.

Communications and Signal Processing
Second Year: Selected from APh 17 abc, APh 23, APh 24, EE/CS 53
Third and Fourth Year: EE 112 abc, EE/Ma 126, EE/Ma 127 ab, EE 161, EE 162, EE 163 ab, EE 164, EE 167, APh/EE 130 abc, and selections from CNS/EE 124, APh 130 b, APh/EE 132, EE/CS 54, Ma 112 a

Control
Second Year: APh 17 abc
Third and Fourth Year: CDS 110 ab, CDS 111, and selections from CDS 113 ab, CDS 112, EE 112 abc, EE 162, EE 164

Electronic Circuits
Second Year: APh 17 abc
Third and Fourth Year: CDS 111, EE 112 abc, EE 114 ab, and selections from EE 50, EE 55, EE 105, CDS 113 ab, EE/Mu 107 abc, EE 153, CS/EE 181 abc, CNS/CS/EE 182 abc, CS 185 abc, APh 183 ab

Microwave and Radio Engineering
Second Year: APh 23, APh 24, APh 17 abc
Third and Fourth Year: EE 153, EE 157 abc, EE 158, APh/EE 130 abc, APh/EE 132, APh 183 ab

Optoelectronics
Second Year: APh 23, APh 24, APh 17 abc
Third and Fourth Year: APh 124, APh/EE 130 abc, APh/EE 132, APh 105 abc, APh 114 abc, APh/CNS/EE 133, APh 183 ab, APh 190 abc, EE 153

Solid-State Electronics
Second Year: APh 17 abc
Third and Fourth Year: EE 185 ab, APh 183 ab, and selections from APh 105 abc, APh 114 ab, EE 153

Engineering and Applied Science Option

The engineering and applied science option offers the opportunity for study in challenging areas of science and technology. In addition to such engineering disciplines as mechanical or civil engineering, computer science, etc., the student may undertake work in such diverse fields as environmental engineering science, energy engineering and thermal science, the physics of fluids, earthquake

engineering, aerodynamics, solid mechanics, materials science, elasticity and plasticity, the theory of waves and vibrations, mechanical systems, and engineering design. The option in engineering and applied science offers an unusually broad curriculum that permits students to tailor a course of study to their individual needs as well as pursue one of the more traditional engineering curricula.

The aim of the undergraduate program in engineering and applied science at Caltech 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 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.

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 engineering and applied science 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 a certain 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.

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 subjects with the prefix Ae, AM, APh, CDS, CE, ChE, CNS, CS, E, EE, ES, Env, JP, MS, or ME may, at the discretion of the division faculty, be refused permission to continue the work of that option.

Option Requirements

1. E 10.
2. ACM 95 abc or Ma 108 abc or Ma 109 abc. Neither sequence of courses may be taken pass/fail.
3. 126 additional units in courses in the following: Ae, AM, APh, CDS, CE, ChE, CNS, CS, E, EE, ES, Env, JP, MS, or ME. Note that the student cannot exercise the pass/fail option on any courses offered to meet this requirement.

4. 9 units[1] of courses taken from the following list: APh 24, APh 77, APh 124, APh/MS 141, Ae/APh 104 bc, CDS 111, CE 95, CE 97, CE 180, CS 40 ab, CS 47, CS 134 b, CS/CNS 171, 173, and 174, CS/EE 137 b , EE 90, EE 91 ab, Env 116, Env 143, MS 90, MS 125, ME 72, ME 90 bc, ME 96.
5. 9 units[1] of additional laboratory[2], excluding those for which freshman laboratory credit is allowed.
6. Passing grades must be earned in a total of 486 units, including courses listed above.

[1] *These units will partially satisfy requirement 3 when taken from the list in item 4.*
[2] *These electives must either be from the list in item 4 or they must be from courses with the word "laboratory" in the title.*

All students selecting the E&AS option should have a minimum competency in computer science by the end of the first year. This competency may be established in one of two ways. Students with little or no programming skills should take CS 1, 2 in their freshman year. Students possessing basic programming skills may omit CS 1. Students especially interested in computer science should take the full sequence of CS 1, 2, 3 in consecutive terms of their freshman year.

Concentrations within the E&AS option

Students who wish to focus their studies in a particular field of engineering and applied science may declare one concentration within the E&AS option. Currently, two concentrations are available—aeronautics and mechanical engineering. Students who satisfy their E&AS option requirements using courses from the lists below will have both the option (E&AS) and the concentration (aeronautics or mechanical engineering) noted on their transcript.

Aeronautics Requirements

A student can earn a concentration in aeronautics by completing the following courses as part of the option requirements for E&AS: AM 35 abc, ME 18 ab, ME 71, ME 19 abc, MS 15 ab, AM/ME 65, CDS 110 a, and Ae 103 abc.

Mechanical Engineering Requirements

A student can earn a concentration in mechanical engineering by completing the following courses as part of the option requirements for E&AS:

1. CS 1 or CS 2, AM 35 abc, ME 18 ab, ME 19 ab, ME 70, ME 71, AM/ME 65 (or MS 15 a), and CDS 110 a.
2. 9 units of CE/ME 96 and 9 units of additional laboratory (e.g., ME 72 or CE/ME 97), or an experimental senior thesis (ME 90 abc).

3. 18 units—in addition to those listed in items (1) and (2)—chosen from ME 19 c, ME 20, ME 90 abc, ME 91 abc, ME 101 abc, ME 115 ab, ME 119 abc, ME 171, CDS 110 b, CDS 111, AM 102 abc, AM 151 abc, or an advanced engineering course approved by the mechanical engineering faculty.

Typical Course Schedules

Typical course schedules and typical course sequences are given on the following pages for several engineering disciplines. These should be considered not as requirements but as guides, with the details to be worked out by the student and his or her adviser.

	Units per term		
	1st	*2nd*	*3rd*
Second Year			
Ma 2 ab	9	9	-
Ph 2 ab	9	9	-
Humanities 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
Humanities Electives	9	9	9
Electives	24	24	24
	45	45	45
Fourth Year			
E 10	-	3	-
Humanities Electives	9	9	9
Electives	33	33	33
	42	45	42

Aeronautics (suggested schedule of requirements)

	First Term	*Second Term*	*Third Term*
First Year[1]	Elective	E 5	Elective
Second Year[2]	AM 35 a	AM 35 b	AM 35 c
	ME 18 a[3]	ME 18 b[3]	ME 71
Third Year[4]	ME 19 a	ME 19 b	ME 19 c
	MS 15 a	MS 15 b	
Fourth Year[5]	Ae 103 a	Ae 103 b	Ae 103 c
	CDS 110 a	AM/ME 65	

[1] *Recommend two courses selected from CS 1, CS 2.*
[2] *Suggested electives include APh 23, APh 24.*
[3] *APh 17 abc is a suggested alternative for ME 18 ab.*
[4] *Suggested electives include APh 50 abc, CE 97, CS 3, EE 14 abc, MS 90.*
[5] *Suggested electives include Ae/APh 101 abc, Ae/AM 102 abc, Ae/APh 104 abc, Ae 107,* ACM *101 abc, CE/ME 101 abc, CS 20 abc, EE 32 ab, JP 121 abc, ME 20 ab, ME 96, ME 115, ME 171 ab.*

Applied Mechanics

	First Term	*Second Term*	*Third Term*
First Year[1]	Elective	E 5	Elective
Second Year[2]	AM 35a	AM 35 b	AM 35 c
	ME 18 a	ME 18 b	Electives
Third Year[3]	Elective	AM/ME 65	AM/ME 66
	ME 19 a	ME 19 b	ME 19 c
Fourth Year[4]	AM 151 a[5]	AM 151 b[5]	AM 151 c[5]
	Ae/AM 102 a[5]	Ae/AM 102 b[5]	Ae/AM 102 c[5]

[1] *Recommend one course per term selected from CS 1, CS 2, E 5, Env 1, Ge 1.*
[2] *Recommended electives include Bi 1, ME 71, MS 15 ab, MS 90.*
[3] *Recommended electives include APh 25, MS 15 ab, MS 90, Ph 106 abc.*
[4] *Recommended electives include AM 135 abc, MS 120, CE/ME 101 abc, CE 97, ME 96, CDS 110 ab, CDS 111, and AM 125 abc or* ACM *101 abc.*
[5] *Both Ae/AM 102 abc and AM 151 abc are strongly recommended.*

Civil Engineering (a)
Structural and Soil Mechanics

	First Term	*Second Term*	*Third Term*
First Year[1]	Elective	E 5	Elective
Second Year[2]	AM 35 a	AM 35 b	AM 35 c
	ME 18 a	ME 18 b	Electives
Third Year[3]	CE 90 a	CE 90 b	CE 90 c
	ME 19 a	ME 19 b	AM/ME 66
	Elective	AM/ME 65	Elective
Fourth Year[4]	AM 151 a	AM 151 b	AM 151 c
	Ae/AM 102 a	Ae/AM 102 b	Ae/AM 102 c
	CE 115 a	CE 115 b	CE 150

[1] *Recommend one course per term selected from CS 1, CS 2, E 5, Env 1, Ge 1.*
[2] *Recommended electives include ME 71, MS 15 ab, MS 90.*
[3] *Recommended electives include CE 97, ME 96, MS 15 ab, MS 90.*
[4] *Recommended electives include CE/ME 101 abc, CE 97, CE 113 ab, CE 160 abc, CE 180, CE 181, Env 112 abc, ME 96.*

Civil Engineering (b)
Hydraulics and Water Resources

	First Term	*Second Term*	*Third Term*
First Year[1]	Elective	E 5	Elective
Second Year[2]	AM 35 a	AM 35 b	AM 35 c
	ME 18 a	ME 18 b	Electives
Third Year[3]	CE 90 a	CE 90 b	CE 90 c
	ME 19 a	ME 19 b	ME 19 c

Fourth Year[4]	CE/ME 101 a Env 112 a CE 115 a	CE/ME 101 b Env 112 b CE 115 b	CE/ME 101 c Env 112 c CE 150

[1] *Recommend one course per term selected from CS 1, CS 2, E 5, Env 1, Ge 1.*
[2] *Recommended electives include ME 71, MS 15 ab.*
[3] *Recommended electives include CE 97, ME 96, MS 15 ab, MS 90.*
[4] *Recommended electives include Ae/AM 102 abc, AM 151 abc, CE 97, CE 113 ab, Env 146, Env 175 abc, ME 96.*

Computer Science

	First Term	*Second Term*	*Third Term*
First Year	CS 1	CS 2	CS 3
Second Year	CS 20 a CS/Ma 6 a	CS 20 b CS/Ma 6 b	CS 20 c CS/Ma 6 c
Third Year[1]	CS 138 a Electives	CS 138 b Electives	CS 138 c Electives
Fourth Year[1]	Electives	Electives	Electives

[1] *At least one 100-level CS laboratory course, and at least one 100-level CS nonlaboratory course.*

Environmental Engineering Science

	First Term	*Second Term*	*Third Term*
First Year[1]	Elective	Elective	Env 1
Second Year	Me 18 a[2] Elective[3]	Me 18 b[2] Elective[3]	Electives[3]
Third Year	Me 19 a[4] Electives[5]	Me 19 b[4] Electives[5]	CE 97 Electives[5]
Fourth Year	Electives[5]	Electives[5]	Electives[5]

[1] *Recommend additional electives selected from Bi 9, ChE 10, CS 1, CS 2, E 5, Ge 1.*
[2] *APh 17 abc and ChE 63 ab are alternatives.*
[3] *Recommend one course per term selected from Ch 14, Ch 15, Ch 41 abc, Env 144, Env 145 ab, MS 15 a.*
[4] *ChE 103 abc is an alternative.*
[5] *Junior and senior electives should be individually planned with the adviser to provide coherent sequences depending on the student's special interests (e.g., air quality, water quality, fluid mechanics and hydrology, and applied biology). Strongly recommended electives by area are air quality, ChE/Env 157, 158, 159; water quality, Env 142 ab, 143; fluid mechanics and hydrology, Env 112 abc; and applied biology, Env/Bi 166, 168. Other recommended electives include:* ACM *101 abc,* ACM *104,* ACM *105, Bi/Ch 110 abc, Ch 21 abc, Ch 24 ab, CE 113 ab, CE/ME 101 abc, Env 146, Ge 152 abc.*

Materials Science

	First Term	*Second Term*	*Third Term*
First Year[1]	APh 9 a	E 5[2]	ChE 10
Second Year	APh 17 a MS 15 a	APh 17 b MS 15 b	APh 17 c MS 90
Third Year[3]	MS 131 AM 35 a	MS 132 AM 35 b	MS 133 AM 35 c APh 25
Fourth Year[3]	Electives	APh/MS 141 Electives	Electives MS 124

[1] *Recommend at least one term from CS 2.*
[2] *Or APh 9 b.*
[3] *Recommended additional electives to be agreed upon by student and adviser. Electives of general interest may be chosen from the Caltech* Catalog.

Mechanical Engineering (suggested schedule of requirements)

	First Term	*Second Term*	*Third Term*
First Year	CS 1		
Second Year	AM 35 a ME 18 a	AM 35 b ME 18 b	AM 35 c ME 71[1]
Third Year[2]	ME 19 a	ME 19 b ME 70	Add. Lab.[1] ME/CE 96 or CE/ME 97
Fourth Year[2]	CDS 110 a Advanced Electives	AM/ME 65[3] Advanced Electives	

[1] *Or ME 90 abc, senior thesis.*
[2] *See mechanical engineering requirement 3.*
[3] *Or MS 15 a.*

Geology, 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, and build upon, the 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 emphasized 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 (including geobiology), geo-

physics, planetary science, and geochemistry. 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. For students beginning their junior year, it is possible to complete the requirements for each of the options within two years, but there are benefits from starting with Ge 11 abc in the sophomore year.

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.

Division and Option Requirements

Typical Course Schedule

Division Requirements (All Options)

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ge 11 ab, Ge/Ay 11 c	Introduction to Earth and Planetary Sciences	9	9	9
Third Year				
ACM 95 abc[1]	Introductory Methods of Applied Mathematics	12	12	12
Fourth Year				
Ge 109	Oral Presentation	3	-	-

[1] *For students entering some GPS fields, e.g., geobiology, a course sequence such as Bi/Ch 110, 111, and 113 may be substituted on petition to the Academic Committee.*

Geology Option Requirements

		Units per term		
		1st	*2nd*	*3rd*
Third Year				
Ge 112	Geomorphology and Stratigraphy	12	-	-
Ge 114	Mineralogy	12	-	-
Ge 106	Structure and Tectonics	-	12	-
Ge 115 a	Igneous Petrology	-	12	-
Ge 111 a	Applied Geophysics Seminar	-	-	6
Ge 115 b	Metamorphic Petrology	-	-	12
		24	24	18

Summer (Recommended in Third Year)				
Ge 111 b	Applied Geophysics Field Course	-	-	9
Ge 120	Summer Field Geology	-	-	12
		-	-	21
Fourth Year				
Ge 121 ab	Advanced Field and Structural Geology	12	-	12

Geochemistry Option Requirements

Second Year				
Ch 4 a	Synthesis and Analysis of Organic and Inorganic Compounds	-	-	9
Ch 41 abc	Organic Chemistry	9	9	9
		9	9	18
Third Year				
Ch 14	Chemical Equilibrium and Analysis	6	-	-
Ch 21 abc	The Physical Description of Chemical Systems	9	9	9
Ch 4 b	Synthesis and Analysis of Organic and Inorganic Compounds	-	9	-
	Geochemistry Electives[2]	9	9	9
		24	27	18
Fourth Year				
Ch 6 ab	Application of Physical Methods to Chemical Problems	-	10	10
Ch 15	Chemical Equilibrium and Analysis Laboratory	10	-	-
	Geochemistry Electives[2]	9	9	9
		19	19	19

[2] *Geochemistry electives (selected in consultation with adviser): Ge 114, Ge 115 ab, Ge/Ch 127, Ge/Ch 128, Ge 140 ab, Ge/Env 149, Ge/Env/Ch 171, Ge/Env/Ch 172, Env 142 ab, Env/Ge 148 b.*

Geophysics Option Requirements

		Units per term		
		1st	*2nd*	*3rd*
Third Year				
Ph 106 abc	Topics in Classical Physics	9	9	9
Ge 111 a	Applied Geophysics Seminar	-	-	6
Ge 66	Planet Earth	-	9	-
		9	18	15
Summer (Recommended in Third Year)				
Ge 111 b	Applied Geophysics Field Course	-	-	9

Fourth Year				
	Geophysics Electives[3]	18	9	9

[3] *Geophysics electives (selected in consultation with adviser): Ge 166, Ge 176, Ge 161, Ge 180, Ge 165, Ge 168, Ge 169.*

Planetary Science Option Requirements

Third Year				
Ph 106 abc	Topics in Classical Physics	9	9	9
	Required Option courses[4]	9	9	9
	Option Electives[5]	9	-	-
		27	18	18
Fourth Year				
	Option Electives[5]	9	9	9
	Outside Electives[6]	9	9	9
		18	18	18

[4] *Three required courses (27 units) from Env/Ge 148 abc, Ge/Ay 103, Ge/Ay 132, Ge/Ay 133.*

[5] *Recommended option electives (selected in consultation with adviser): Ge/Ch 128, Ge 131, Ge/Ay 132, Ge/Ay 133, Env/Ge 148 abc, Ge 151, EE/Ge 157 abc, Ge 225 abc.*

[6] *Recommended electives outside option (selected in consultation with adviser): AM 35 abc, APh 17 abc, APh 25, Ch 6 ab, Ch 21 abc, CS 1, CS 2, CS 3, Ma 112 ab, ME 18 ab, ME 19 abc, Ph 103 abc.*

History Option

History majors must take not less than 99 units of history courses (including Freshman Humanities) during their four years as undergraduates. Of these, not less than 45 *must* be in junior and senior tutorial (H 97 ab and H 99 abc), and another 18 *may* be in H 98 ab if students wish and their instructors agree.

The courses and tutorials in the history option concentrate on three areas: Europe, the United States, and Asia. Each history major will concentrate in one of these areas and write a research paper in it; each student must also take at least 36 units of history in other areas as approved by the adviser or as required by the history option.

A student considering the history option when he or she comes to Caltech will be well advised to take one sequence of Hum 2, 6, 7, 8, or 9. In the sophomore year the student should take upper-level history courses, but this is also a good time to pursue the study of literature or philosophy, to begin or continue a foreign language (particularly desirable if the area of concentration is to be Europe or Asia), 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, exploring this area through regular course work supplemented during the second and third terms by tutorial study in H 97 ab. At the beginning of the senior year, a history major will enroll in H 99 abc and be assigned to a

faculty member in the student's chosen area. The first term will be devoted to preparation, the second to research, and the third to the writing of a substantial research paper.

Since statistics can be a useful tool in historical analysis, the option recommends that some of the science and math courses that a history major takes beyond the sophomore year (to satisfy the 54-unit Institute requirement) be in that area. Students who wish to write their senior research papers in the history of science are encouraged to use the rest of the 54 units to advance their understanding of one or two particular scientific disciplines.

Option Requirements

1. H 97 ab, H 99 abc. H 99 c fulfills the Institute science communication requirement.
2. 54 additional units of history courses (including, if appropriate, H 98 ab), of which 36 must be in an area or areas other than the area of concentration.
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 Ay 1, Bi 7, EE 14, Env 1.
4. Passing grades must be earned in a total of 486 units, including the courses listed above.

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 below). 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 pro-

fessorial 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.
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.

Literature Option

Students majoring in literature can take a broad range of literature courses or, if they wish, concentrate on American, English, or comparative (cross-national) literature. All majors are assigned an

adviser who will help them select the courses best suited to their needs, including courses in fields closely related to literature. Majors will be expected to consult their adviser before registering for each quarter's work. Those who are preparing for graduate work should take more than the minimum requirements listed below, and should be prepared to take courses in several periods of English literature and in the literature of one or more foreign languages. All literature courses must be taken for grades.

Option Requirements

1. 108 units in the Lit 98–180 group of courses (or, with authorization, certain Hum courses), to be taken under the guidance of the major adviser, and including at least one quarter of Lit 114 (Shakespeare) and Lit 99. An additional quarter concentrating on a second major author (e.g., Chaucer, Milton, Wordsworth, Melville, Joyce) is also recommended. L 99 fulfills the Institute science communication requirement.
2. 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 Ay 1, Bi 7, EE 14, Env 1.
3. Passing grades must be earned in a total of 486 units, including the courses listed above.

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 exceptionally well in their freshman and sophomore years, they should not contemplate specializing in mathematics. An average of at least "B" in mathematics courses is required of students in order to major 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, software engineering, 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 of becoming 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, com-

puter science, electrical engineering, and computation and neural systems.

Each term during 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.

Attention is called to the fact that students whose grade-point averages are 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 the work of the mathematics option.

Option Requirements

1. Ma 5 abc, Ma 108 abc, Ma 109 abc, Ma 10.
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. Courses in other options with high mathematical content may be used to fulfill this requirement with the approval of the executive officer for mathematics.
5. The courses that are used to meet requirements 2, 3, 4 must include two quarters (18 units) of a single course, chosen from the mathematics 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.)
6. Passing grades must be earned in a total of 483 units, including the courses listed above.

Typical Course Schedule

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
Ma 2 ab	Linear Algebra, Statistics, and Differential Equations (4-0-5)	9	9	-
Ph 2 ab	Statistical Physics, Waves, and Quantum Mechanics (4-0-5)	9	9	-
Ma 5 abc	Introduction to Abstract Algebra (3-0-6)	9	9	9
	Humanities Electives	9	9	9
	Electives[1]	9	9	27
		45	45	45

Third Year				
Ma 10	Oral Presentation	3	-	-
Ma 108 abc	Classical Analysis (3-0-6)	9	9	9
Ma/CS 6 ac	Introduction to Discrete Mathematics (3-0-6)	9	-	9
	Humanities Electives	9	9	9
	Electives[1]	18	27	18
		48	45	45
Fourth Year				
Ma 109 abc	Introduction to Geometry and Topology (3-0-6)	9	9	9
	Humanities 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 items 4, 5 under option requiqrements.*

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 wide 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. 18 units of Ph 78, or 18 units from Ph 77 and Ph 76, or 9 units from Ph 77 or Ph 76 and 9 units from APh 77 or Ay 105.
5. Ph 70.
6. Ph 106 and Ph 125.

Electives

7. 54 units, in addition to the above, of any of the following: Ph 78, Ph 79, any Ph or APh course numbered 100 or above, or ACM 101. Students wishing to apply more than 9 units of Ph 171, Ph 172, or Ph 173 toward this 54-unit requirement must petition the Physics Undergraduate Committee for approval. Nine units toward the 54 elective units will be given for taking Ph 5. Nine units toward the 54 will be given for taking three terms from Ph 76 and Ph 77 combined. Other courses in other departments with substantial physics content may be approved by the Physics Undergraduate Committee in individual cases; seniors must submit their petition for this purpose before the first day of the third term. The student cannot exercise a pass/fail option for any courses offered to meet this requirement.
8. 27 units of science or engineering electives outside of Ph, APh, Ma, and ACM. Core Science Electives can be counted. If the student has taken Bi 1, then only 18 units are required.
9. Passing grades must be earned in a total of 486 units, including the courses listed above.

[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.*

Typical Course Schedule[1]

	Units per term		
	1st	*2nd*	*3rd*
Second Year			
Ph 12	9	9	9
Ma 2 ab	9	9	0
Humanities	9	9	9
Physics Laboratory	0	9	9
Electives	12	9	9
Core Science Elective if not taken earlier	0	0	9
	39	45	45

[1] *In addition to the required courses listed here, facility with computer programming at the level of CS 1 is strongly recommended, and further computer-related course work such as CS 2, or Ph 20–22 is highly desirable. Facility with electronics at the level of Ph 5 also is recommended.*

Third Year			
Ph 106	9	9	9
Ph 125	9	9	9
ACM 95 or Ma 108 or Ma 109	12	12	12
Humanities	9	9	9
Electives	9	9	9
	48	48	48
Fourth Year			
Ph 77 or Ph 76	9	9	0
Advanced Physics Electives	18	18	18
Electives	9	9	18
Humanities	9	9	9
Ph 70	0	3	0
	45	48	45

Science, Ethics, and Society/History and Philosophy of Science Option and Minor

The option in science, ethics, and society (SES) provides students with a broad historical and philosophical education in the social, economic, ethical, and political issues that have arisen in the modern world in connection with the advance of science and technology. The program is concerned with study of the long-term development of science and technology and with the evolution of disputes over ethics and policy in areas such as research and development, technological innovation, energy supply and conservation, the environment, and biomedicine. The curricular core of the program resides in historical and/or philosophical study of subjects such as the Scientific Revolution, the politics of research and development, the social uses of biological knowledge, the nature of scientific explanation, and the evolution of theories of cognition; but the program also takes up contemporary issues concerning science and technology, treating them in philosophical, ethical, and historical perspective. The option thus focuses on the acquisition of broad basic knowledge about persistent issues in the affairs of science, technology, and society so as to enable students to deal with such issues in the future, whatever particular form they may take. The option offers students the advantage of developing special literacy in and understanding of issues of science and society, because the program combines courses that directly address such issues with the strong technical background gained at Caltech. It provides excellent preparation for students going into law, business, medicine, and public affairs, as well as solid preparation for graduate work in history and/or philosophy of science.

SES may be pursued as a minor concentration by undergraduates who are taking degrees in science, mathematics, or engineering. The SES minor is a valuable supplement to a technical degree, since it helps equip students to meet the nontechnical social chal-

lenges that people in technical careers increasingly encounter. It also enables students to pursue a guided coherent and cumulative program of study that culminates in the writing of a research paper and that provides advantageous preparation for students who may choose to pursue careers in law, business, public policy, and history or philosophy of science. Students who successfully complete the SES minor will be recognized with official credit for the achievement on their transcripts.

Option Requirements

1. SES 10 ab, SES 102 abc, and SES 103 (normally for 9 quarters). SES 102 c fulfills the Institute science communication requirement.
2. Two advanced SES courses in the history of science, chosen from SES/H/Lit 128, SES/H 156, SES/H 157, SES/H 158, SES/H 159, SES/H 160 ab, SES/H 162, SES/H 163, SES/H 164, SES/H 165, SES/H 166, SES/H 168, SES/H 169.
3. Two advanced history courses.
4. Two advanced philosophy courses.
5. Two advanced courses in philosophy of science or ethics, chosen from SES/Pl 122, SES/Pl 125, SES/Pl 126, SES/Pl 127, SES/Pl 131, SES/Pl 169, SES/Pl 185.
6. 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.
7. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Explanatory Notes

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. Students electing the SES option would normally take SES 10 ab by the end of the sophomore year. This is a two-quarter introductory course, one quarter of which emphasizes historical issues, the other quarter of which focuses on philosophical ones.

Students in the option will normally take SES 103 each quarter, beginning in the sophomore year. This is a lecture series featuring outside speakers roughly four times per quarter that introduces students to a broad variety of SES-related topics past and present. It is graded on attendance.

SES 102 abc is a three-quarter course devoted to the writing of a senior research paper. The first two quarters are taught primarily as a tutorial, with students developing their paper topics under the guidance of a faculty adviser; the third quarter will be taught as a seminar in which the students discuss and criticize each other's developing papers. The senior research paper stresses independent

work and can cover any one of a number of topics from a historical and/or philosophical/ethical perspective, including biotechnology, biomedicine, the environment, science and national defense, the historical politics of research and development, Big Science, the nature and growth of scientific knowledge, cosmology, or science and theories of cognition, language, and perception. Among the resources available for writing the senior paper are the Caltech Archives, which contain a substantial collection of rare books in the history of science going back to the 16th century, and which house the correspondence and other papers of a number of distinguished scientists, including George Ellery Hale, Robert Millikan, Richard P. Feynman, Lee A. DuBridge, and Max Delbrück. The materials in the Caltech Archives throw considerable light on the development of key fields in modern science—for example, astrophysics, quantum mechanics and relativity, molecular biology, and geology and planetary science—and are rich in information on topics such as the relationship of science to government and industry.

Typical Course Schedule

First Year

It is recommended that students take the following courses: history of early modern Europe or the American Revolution; introduction to or history of philosophy; and Ec 11 or PS 12. Alternatively, they may take SES 10 ab as their freshman humanities.

		Units per term		
		1st	*2nd*	*3rd*
Second Year				
SES 10 ab	Introduction to Science, Ethics, and Society (if not taken first year)	9	9	-
	Advanced Philosophy or History	-	-	9
SES 103	Lecture Series (1-0-0)	1	1	1
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ph 2 ab	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	-
	Menu Course	-	-	9
	Electives	18	18	27
		46	46	46

It is recommended that one of the electives be either Ec 11 or PS 12, whichever one has not been taken in the freshman year.

Third Year				
SES 103	Lecture Series (1-0-0)	1	1	1
	Advanced SES/History	9	9	9
	Advanced SES/Philosophy	9	9	9
	Science, Math, Engineering	9	9	9
	Electives	18	18	18
		46	46	46

Fourth Year				
SES 103	Lecture Series (1-0-0)	1	1	1
SES 102 ab	Senior Research Tutorial (1-0-8)	9	9	-
SES 102 c	Senior Research Seminar (2-0-7)	-	-	9
	Advanced SES/History or Philosophy	9	-	-
	Science, Math, Engineering	9	9	-
	Electives	18	27	36
		46	46	46

It is recommended that students choose their advanced social science electives from among courses that will enlarge their perspective on topics related to SES (for example, Ec 118, Ec/SS 128, Ec/SS 129, Ec/SS 130, PS 120, PS 121, PS 122, An 22, An 123).

SES Minor Requirements

Undergraduates taking the SES minor will pursue a two-part program of study using the 108-unit humanities and social sciences (HSS) requirement in a way that is tailored, with the help of a program adviser, to their particular interests. The first part is introductory, comprising SES 10 ab as well as general but related courses in humanities and social sciences selected so as to develop a coherent and solid foundation for work in an area of SES concentration. The second part consists of advanced courses clustered in an area of concentration such as those described in the option requirements. To this end, SES minor students are required to complete at least one advanced course in the history of science and one in the philosophy of science or ethics. Qualifying history courses are SES/H/Lit 128, SES/H 156, SES/H 157, SES/H 158, SES/H 159, SES/H 160 ab, SES/H 162, SES/H 163, SES/H 164, SES/H 165, SES/H 166, SES/H 168, SES/H 169. Qualifying philosophy courses are SES/Pl 122, SES/Pl 125, SES/Pl 126, SES/Pl 127, SES/Pl 131, SES/Pl 169, SES/Pl 185.

In addition to completing the 108-unit HSS requirement, SES undergraduates must participate in their junior and senior years in SES 103 and complete SES 102 bc. The research paper expected of SES minor students will be shorter than that expected of students in the option; hence, only the second two quarters of SES 102 are required. The remaining choice of courses in both humanities and social sciences will be determined by a student's expected SES concentration. It is recommended that SES-minor students use their social science requirement to develop a strong grounding in economics and politics and that they take at least one course in literature (Lit 138 and/or Lit 127 are recommended).

All SES courses required for the SES minor must be taken for grades, with the exception of SES 103.

Course of Minor Study
During four years, the normal SES minor course of study will resemble the following:

1st Year
1. Freshman history and/or philosophy (2 quarters; 18 units). May also be taken in the first year.
2. Introductory economics or political science (1 quarter; 9 units).

2nd Year
1. SES 10 ab, Introduction to Science, Ethics, and Society (2 quarters; 18 units).
2. Social science (1 quarter; 9 units).
3. SES 103 lecture series (3 quarters; 3 units) (recommended but optional).

3rd Year
1. History or philosophy of science (1 quarter; 9 units).
2. Advanced humanities (1 quarter; 9 units).
3. Advanced social science (1 quarter; 9 units).
4. SES 103 lecture series (3 quarters; 3units).

4th Year
1. History or philosophy of science (1 quarter; 9 units).
2. Advanced humanities (1 quarter; 9 units).
3. Advanced social science (1 quarter; 9 units).
4. SES 102 bc research tutorial and seminar (2 quarters; 18 units).
5. SES 103 lecture series (3 quarters; 3 units).

Social Science Option

The social science program is designed to provide undergraduates with multidisciplinary training in social science. The program focuses on the processes of social, political, and economic change and the analytical methods used by social scientists to describe and predict them. The program is designed to be sufficiently flexible to provide an excellent preparation for students intending to attend graduate school in any social science discipline, or in law or business.

Option Requirements
1. Ec 11, PS 12, Ec 121 a, Ma 112 a, Ec 122, PS/Ec 172, Ec/SS 20.
2. One of the following: An 22, An 101, or Psy 15.
3. 45 additional units of science, mathematics, and engineering courses. The requirement cannot be satisfied by courses listed as satisfying the introductory laboratory requirement or by any course with a number less than 10.
4. 54 additional units of social science courses, which include any

course listed under the following headings: anthropology, economics, law, political science, psychology, and social science. (Courses that are used to fulfill the Institute upperclass social science requirement [courses numbered 100 and above] will also count toward the 54 additional units required under the economics and social science options.)

5. 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				
Ec 11	Introduction to Economics (3-0-6)	9	-	-
PS 12	Introduction to Political Science (3-0-6)	-	-	9
Ma 2 ab	Sophomore Mathematics (4-0-5)	9	9	-
Ph 2 ab	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	-
	Menu Course	-	-	9
	Electives	18	27	27
		45	45	45
Third Year				
Ma 112 a	Statistics (3-0-6)	9	-	-
Ec/SS 20	Oral Presentation	-	-	-
Ec 121 a	Theory of Value (3-0-6)	-	9	-
Ec 122	Econometrics (3-0-6)	-	9	-
PS/Ec 172	Noncooperative Games in Social Science (3-0-6)	-	9	-
An 101 or	Selected Topics in Anthropology (3-0-6)	-	-	-
An 22 or	Introduction to the Anthropology of Development (3-0-6)	9	-	-
Psy 15	Cognitive Psychology (3-0-6)	-	9	-
	Electives	27	9	45
		45	45	45
Fourth Year				
	Electives[1]	45	45	45

[1] *Students may concentrate on research by taking 54 units of supervised research in their senior year.*

Information for Graduate Students

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: Aeronautical 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 2000–2001 are as follows:

Aeronautics	Prof. J. Shepherd
Applied and Computational Mathematics	Prof. Y. Hou
Applied Mechanics	Profs. J. Burdick and T. Heaton
Applied Physics	Prof. H. Atwater
Astronomy	Prof. G. Djorgovski
Biochemistry and Molecular Biophysics	Prof. J.L. Campbell
Engineering Science/Bioengineering	Prof. M. Gharib
Biology	Prof. P. Sternberg
Chemical Engineering	Prof. G. Gavalas
Chemistry	Prof. J. Barton
Civil Engineering	Profs. J. Burdick and T. Heaton
Computation and Neural Systems	Prof. G. Laurent
Computer Science	Prof. P. Schröder
Control and Dynamical Systems	Prof. J. Marsden
Electrical Engineering	Prof. P. P. Vaidyanathan
Environmental Engineering Science	Prof. M. Hoffmann
Geological and Planetary Sciences	Prof. G. Rossman

Materials Science	Prof. B. Fultz
Mathematics	Prof. G. Lorden
Mechanical Engineering	Profs. J. Burdick and T. Heaton
Physics	Prof. F. Porter
Social Science	Prof. C. Camerer

GRADUATE POLICIES AND PROCEDURES

Admission to Graduate Standing

Application

Apply to the Dean of Graduate Studies, California Institute of Technology, 02-31, Pasadena, CA 91125, for an application form for admission to graduate studies. 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 both men and women, including members of minority groups. Students wishing to apply for assistantships or fellowships may do so in the appropriate section of the application for admission. Completed applications are due in the Graduate Office no later than January 15; January 1 for biology and computer 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. Although the application form asks the applicant to state his or her intended major field of study and special interests, the application may actually be considered upon request by two or more options.

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.

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.

Required Tests

The Graduate Record Examination is very strongly recommended by all options, and scores are required by most options as part of the application for graduate admission.

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). Nearly all successful applicants have a computer-based Test of English as a Foreign Language (TOEFL) score better than 250, or a paper-based score better than 600. The overall IELTS band score should be at least 7. 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.

The testing schedules for and information on the TOEFL, TWE, and TSE may be obtained by writing to TEOFL, Educational Testing Service, Princeton, NJ 08540. They are also available on-line at 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 on-line at 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 non-credit courses in English as a Second Language (ESL).

Special Students

Students may be admitted in exceptional cases as special graduate students to carry out full-time studies at the Institute without being candidates for a degree from Caltech. 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.

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 Aeronautical 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 and file a program card in the registrar's office 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.

Mail registration is provided for graduate students during a two-week period near the end of the previous quarter. A late registration fee of $50 is assessed for failure to register on time. 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. This registration program card must be signed by the student's adviser. An adviser is assigned to each entering graduate student by the option representative. In most options a new adviser is assigned when the student begins research. Only members of the professorial faculty may serve as advisers. With the approval of the dean of graduate studies, any graduate student whose work is not satisfactory may be refused registration at the beginning of any term by the division in which the student is doing his or her major work.

In registering for research, students should indicate on their program card 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.

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 (see page 230).

All students in residence must be registered. A registration card for summer research must be filed with the registrar's office in May. 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 approved sabbatical. A sabbatical for medical or other reasons may be approved for up to one year at a time. Sabbatical will be approved to meet military obligations, and tuition adjustments will be made if the sabbatical must be initiated within a term. (See page 132.) An approved sabbatical indicates that the student can return to the option at the end of the sabbatical. 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 sabbatical without jeopardizing their visa status. Students who hold nonimmigrant visas must meet with the director of international student programs to determine visa status during the sabbatical. If you plan to

change your visa status during your sabbatical, you must submit copies of your Change of Status, or other evidence of your new status, to the International Student Programs Office. These requirements will also need to be met prior to the last term for which you are registered at Caltech.

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.

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.

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 the Graduate Student–Faculty Adviser Relationship

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 (see page 215), 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.

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 44–58). 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 Ombudsperson, 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 236–307) and the Student Grievance Procedure (page 58).

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 per-

mission 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 division is required.

Part-time nondegree students are subject to the Honor System (see pages 31–32) 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 he or she maintains 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.

Engineer's Degree

Engineer's degrees are awarded in aeronautical engineering, 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.

Competency in English can be demonstrated in several ways. The student from a non-English-speaking country can meet the oral portion of the requirement by acquiring TSE or SPEAK scores of 50 or above prior to admission; by testing or screening at the time of admission, within the ESL class; or by arranging to take a test with the Office of International Students. A record of

the test scores will be maintained in the Graduate Office and provided to the option representative as required for attesting to preparation for candidacy. The writing portion of the requirement may be demonstrated by a score of 5 or above on the TWE test or by acceptance of the final thesis by the faculty.

Such 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 [minor 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.

The required competency in English can be demonstrated in several ways. The student from a non-English-speaking country can meet the oral portion of the requirement by acquiring TSE or SPEAK scores of 50 or above prior to admission; by testing or screening at the time of admission, within the ESL class; or by arranging to take a test with the Office of International Students. A record of the test scores will be maintained in the Graduate Office and provided to the option representative as required for attesting to preparation for candidacy. The writing portion of the requirement may be demonstrated by a score of 5 or above on the TWE test or by acceptance of the final thesis by the faculty.

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.

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.

Foreign Languages. The Institute believes in the importance of the knowledge of foreign languages and encourages their study as early as possible, preferably before admission to graduate standing. Although there is no Institute-wide foreign-language requirement for the degree of Doctor of Philosophy, graduate students should check for possible specific requirements set by their division or option.

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. 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. (See *Thesis*, below.)

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. 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. Two copies of the thesis are to be submitted in accordance with the regulations governing the preparation of doctoral dissertations, obtainable from the Graduate Office. 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 charge for all students registering for graduate work is currently $19,743 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 $183 a unit for fewer than 36 units, with a minimum of $1,840 a 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.

Each graduate student is required to make a general deposit of $100 to cover loss of, or damage to, Institute property used in connection with work in regular courses of study. Upon completion of graduate work, or upon withdrawal from the Institute, any remaining balance of the deposit will be refunded.

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 term following that in which the past due charges were incurred. Transcripts are not released until all bills due have been paid or satisfactory arrangements for payment have been made 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 Graduate Office.

Expense Summary 2000–2001

General:	
General Deposit	100.00
Tuition	19,743.00
Graduate Student Council Dues	24.00[1]
	$19,767.00

Other:

Books and Supplies *(approx.)*	$1,075.00
Room:	
On-campus graduate room (rates are subject to change)	
For single room	$ 357.00 per month
For suite room	$ 362.00 per month
Avery House	
Avery House single room	$ 457.00 per month
Avery House suite room	$ 480.00 per month
Plus Avery meal plan (M–F)	$ 646.00 per term
Catalina apartments	
For single or married students	
4 bedroom apt.	$ 363.00 per person per month
2 bedroom apt.	$ 430.00 per person per month
1 bedroom apt.	$ 745.00 per apt. per month (plus utilities)

Meals: Available at Chandler Dining Hall, Avery House, or the Athenaeum (members only)

On the following page is a list of graduate fees at the California Institute of Technology for academic year 2000–2001, together with the dates on which these charges are due. Fees are subject to change at the discretion of the Institute.

[1] *Graduate students registered during the summer term are required to pay an additional $8.00 in Graduate Student Council dues.*

First Term	*Fee*
September 25, 2000	
General Deposit	$ 100.00
Tuition	6,581.00
Graduate Student Council Dues	8.00
Second Term	
January 2, 2001	
Tuition	$ 6,581.00
Graduate Student Council Dues	8.00
Third Term	
April 2, 2001	
Tuition	$ 6,581.00
Graduate Student Council Dues	8.00
Tuition fees for fewer than the normal number of units:	
Per unit per term	$ 183.00
Audit Fee, $183 per lecture hour, per term	

Fees for Late Registration. Registration is not complete until the student has personally turned in the necessary registration forms 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.

Graduate Student Council Dues. Dues of $24 are currently charged to each graduate student for the academic year. In addition, $8 is charged to each graduate student registered during the summer. The council uses the dues to support a program of social and athletic activities and other activities of benefit to graduate student life.

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 Institute has one dormitory on campus providing single rooms for 29 graduate students. In September 1984, the Institute completed construction of an apartment complex, Catalina Central, that provides approximately 152 single rooms in four-bedroom furnished units. Catalina North, completed in September 1986, has 156 single rooms in two-bedroom furnished units. Catalina South, completed in September 1988, has 54 single rooms in two-bedroom furnished units, and 29 one-bedroom furnished units. These apartments are also available to married students with families. In addition, there are about 25 spaces for graduate students in Avery House, an innovative residential community of faculty, undergraduates, and graduate students completed in 1996 (see catalog section titled Student Life).

Rates for housing vary, depending upon the accommodations and services provided. A contract is required to live in these houses for the academic year. A $100 deposit must accompany each housing application, and is refunded after check-in. Complete information and reservations can be obtained by writing to the Graduate Housing Office, Mail Code 105-20, California Institute of Technology, Pasadena, CA 91125.

The Institute also owns a limited number of apartments and single-family houses that are available for rental, on a lease basis, to married graduate students. Because of limited availability, there is a waiting list for these properties; priorities are assigned to various categories of students and dependents. For additional information and sign-up forms, contact the Graduate Housing Office, Mail Code 105-20, California Institute of Technology, Pasadena, CA 91125.

The Housing Office maintains a current file of available rooms, apartments, and houses in the Pasadena area. The listings are available on the Web at http://www.caltech.edu/~cabs/. Students preferring to live in non-Institute housing typically pay approximately $450–$475 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. Avery House Dining Hall 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. These applications should reach the Graduate Office by January 15. 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 for one year only; a new application must be filed with option representatives each year by all who desire appointments for the following year, whether or not they already hold such appointments.

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. Students may be allowed to accept outside employment if the time commitment does not interfere with their graduate studies. However, 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 15 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 normally paid monthly.** Assistantships normally permit carrying a full graduate residence schedule also. Only teaching assistants with good oral English are allowed to teach sections.

Teaching assistants must familiarize themselves with Caltech's policy on harassment (see page 49). 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, 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 graduate research assis-tantships.

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 Graduate Office. Loans are not available to first-year international students due to visa restrictions.

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 page 40. 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. Satis-factory 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 research adviser, 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 will receive a tuition refund based on the schedule published on page 131. 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 Graduate 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 Graduate 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.

PRIZES

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.

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 Mathematics
Prizes of up to $500 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.

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.

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. The award consists of a cash award and a certificate.

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 Aeronautical 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.

SPECIAL REGULATIONS OF GRADUATE OPTIONS

Aeronautics

Aims and Scope of Graduate Study in Aeronautics
The Institute offers graduate programs in aeronautics leading to the degrees of Master of Science, Aeronautical Engineer, and Doctor of Philosophy. The programs are designed to provide intense education in the foundations of the aeronautical sciences, with emphasis on research and the experimental method. 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 aeronautics, a student may pursue major study in, for example, one of the following areas: physics of fluids, technical fluid mechanics, structural mechanics, mechanics of materials, mechanics of fracture, aeronautical engineering and propulsion, and aeroacoustics.

While research and course work in aeronautics 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 aeronautics group. 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 lightweight structures, have historically been the focus of research activity in the aeronautics 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 aeronautics courses. Special attention is called to the list of courses numbered Ae 210 or higher.

Examinations, Committees, and Student Responsibilities

To help the student achieve satisfactory progress in his or her academic pursuits, the aeronautics faculty provides for the following committee and individual support.

Upon entering aeronautics 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 Aeronautical 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 engineer's degree.

Students wishing to pursue studies leading to the Ph.D. are required to pass a qualifying examination in the second 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 five-member Candidacy Examination Committee may include the former advisers, or may be formed with different faculty members, one of whom is chosen from outside of aeronautics. 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 five-person committee, which may, but does not need to, have the same constitution as the Candidacy Committee.

Problem and Grievance Resolution within Aeronautics

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 aeronautics 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 aeronautics faculty, acts as an ombudsperson available for student contact. The names of the current student and faculty ombudspersons are available in the aeronautics office.

Degree of Master of Science in Aeronautics

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. 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 108 units must be in the following subject areas:

Fluid mechanics	27 units
Solid mechanics	27 units
Experimental technique and laboratory work	27 units
Mathematics or applied mathematics	27 units

Also, an elective course or course sequence of 27 units must be included, in addition to three units of Ae 150. Each student must have a proposed program approved by his or her 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 Aeronautical 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 working 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 209 abc).

Degree of Aeronautical Engineer

The degree of Aeronautical 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 Aeronautical 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 aeronautics or jet propulsion (Ae 200 or JP 280);
- three units of an advanced seminar such as Ae 208 or Ae/AM 209; and
- satisfactory completion (with a grade of C or better, or Pass) of at least 27 units of aeronautics courses numbered Ae 200 or higher, or Ae 108, Ae120, and Ae 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 Aeronautical Engineer for more than six terms of graduate residence beyond the baccalaureate degree (not counting summer registrations) except by permission after petition to the aeronautics faculty.

Degree of Aeronautical Engineer with Specialization in Spacecraft and Mission Design

The general requirements for this degree are similar to those for the degree of Aeronautical Engineer. However, in this program, the student is choosing a broad area of specialization and must complete one additional required course (Ae 125). The total number of required courses is unchanged. This degree program is

closely coordinated with the local spacecraft industry and the Jet Propulsion Laboratory. Many of the courses are taught by lecturers from JPL. Although the primary emphasis is on the design of spacecraft and missions for unmanned exploration of the solar system, the subjects covered apply to spacecraft quite generally. A primary intention of this program is that students will become firmly grounded in the fundamentals of integrating spacecraft design, propulsion systems, scientific instruments, communications, and mission design.

Students in this program will find access to JPL resources and guidance. Theses will be supervised by Caltech faculty and may be cosupervised by JPL staff.

Admission. Students with a Master of Science degree equivalent to that given by the Institute may seek admission to work for the degree of Aeronautical Engineer with Specialization in Spacecraft and Mission Design.

Program Requirements. The degree of Aeronautical Engineer with Specialization in Spacecraft and Mission Design 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 aeronautics or jet propulsion (Ae 200 or JP 280);
- three units of an advanced seminar such as Ae 208 or Ae/AM 209, or any other by permission of the aeronautics faculty responsible for this program;
- satisfactory completion of the course Ae 125 abc "Spacecraft Systems and Mission Design";
- at least 27 units chosen from the following list:

  JP/Ae 121 abc: Space Propulsion and Trajectory Mechanics
  EE 165: Introduction to Spacecraft Telecommunications
  EE/Ge 157 abc: Introduction to the Physics of Remote Sensing
  EE/Ge 158 abc: Application of Remote Sensing in the Field
  Ge 167: Planetary Physics
  Ge/Ay 103: Introduction to the Solar System
  Ph 224 abc: Space Physics and Astronomy
  CS 181 abc: VLSI Design Laboratory
  CDS 111: Applications of Control Technology
  CDS 140: Introduction to Dynamics
  CDS 212: Introduction to Modern Control

A proposed program conforming to the above regulations must be approved by the student's academic adviser prior to 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. The stu-

dent will have an advisory committee consisting of three academic faculty or, if appropriate, two academic faculty and one staff member from JPL or industry.

No student will be allowed to continue to work toward the degree of Aeronautical Engineer with Specialization in Spacecraft and Mission Design for more than six terms of graduate residence beyond the baccalaureate degree (not counting summer registrations) except by permission after petition to the aeronautics faculty.

Degree of Doctor of Philosophy in Aeronautics

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 aeronautics, 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 any or all of the following: (a) establishing the student's ability to formulate research plans, (b) determining the extent of the student's knowledge in his or her field of interest, and (c) determining the student's ability to use mathematical and physical principles for original work. The qualifying examination generally covers the following broad subjects:

a. Mathematics/Applied and Computational Mathematics
b. Fluid Mechanics/Propulsion/Thermodynamics
c. Solid Mechanics/Structures/Materials
d. Applied Aeronautics/Mechanics/Controls
e. Physics/Applied Physics

The examinations are offered all on one or two days, during the first half of the winter term, in the second year of graduate residence at the Institute.

A student is examined on three of these topics, selected with the approval of the adviser, with the following restrictions:

1. The mathematics/applied mathematics topic is required.
2. A student must choose fluids or solids as the second topic, or both as the second and third topics. Alternate topics must be discussed with the option representative and adviser.
3. The fluids or solids topic, whichever was not covered in the qualifying examination, will then be covered in the candidacy examination (through a corresponding faculty representative on the candidacy committee).

In the event of an unsatisfactory performance, the examining faculty members may permit a repeat examination in the appropriate topic(s). This reexamination must be scheduled prior to finals week of the third term and must be completed before the end of June of the same year.

Candidacy. To be recommended for candidacy for the Ph.D. in aeronautics, the applicant must have satisfactorily completed at least 138 units of graduate work equivalent to the above Master of Science program and must pass one of the following, or its equivalent, with a grade of C or better:

ACM 101 abc Methods of Applied and Computational Mathematics
AM 125 abc Engineering Mathematical Principles
Ph 129 abc Mathematical Methods of Physics

and complete (with a grade of C or better, or Pass)

- at least 45 units of aeronautics courses numbered Ae 200 or higher, or Ae 108, Ae 120, and Ae 160, excluding research and seminars
- an approved subject minor offered outside of aeronautics, or at least 54 units of courses outside of the applicant's chosen discipline and approved by the aeronautics faculty. If, in the latter context a language is chosen, letter grades are required.

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, which includes the topic of mathematics or applied mathematics, 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.

Foreign Languages. The student is encouraged to discuss with his or her adviser the desirability of studying foreign languages.

Thesis and Final Examination. Each candidate is required before graduation 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 aeronautics, on page 237.

Subject Minor in Aeronautics

A student majoring in a field other than aeronautics may, with the approval of the aeronautics faculty, elect aeronautics as a subject minor. A minimum of 54 units in subjects acceptable to the aeronautics faculty is required.

Applied and Computational Mathematics

Aims and Scope of Graduate Study in Applied and Computational Mathematics
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, and engineering applications such as image processing. Entering students should have a background in mathematics, physics, or engineering.

The research areas and interests of the applied and computational mathematics faculty cover a broad spectrum, including asymptotic and perturbation theory, computational fluid mechanics, computational electromagnetics, computational materials science, computational molecular biology, diffusion and transport processes, free surface flows, multiscale problems, and multiresolution analysis and image processing. 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 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 the following courses during their first two years at Caltech. These courses are ACM 101, ACM 102 ab, ACM 103, ACM 104, ACM 110, ACM 111, ACM 112, ACM 113, ACM 210 abc, CS 138 ab, and an application elective course.

Students are expected to take all the 100-level ACM courses and an application elective course during the first year of their graduate studies. The courses ACM 210 abc and CS 138 ab are usually taken during the second year. The application elective course is selected, with the recommendation of the student's advisor, from among a wide range of courses offered by an outside option within the Institute. Students are also expected to take one advanced special topic course during their third and fourth years of graduate study. This is intended to broaden students' knowledge in other application areas, and to prevent undue specialization in their training.

Students who have taken some of the required courses as undergraduates may use them to satisfy the course requirement, 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 (Applied and Computational Mathematics Colloquium) for each quarter that he or she is in residence.

Master's Degree in Applied and Computational Mathematics
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 in Applied and Computational Mathematics

The Oral Candidacy Examination. In order to be recommended for candidacy the student must, in addition to satisfying the general Institute requirements, pass an oral candidacy examination administered by a faculty committee. This examination is normally given at the end of the second graduate year. It is based upon two years' work in the required courses described above (upon special request, examinations may also be given at the end of the fifth quarter of the coursework). The examination will also cover any independent study carried out by the student during his or her first two graduate years.

Advising and Thesis Supervision. Upon passing the oral 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. 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 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 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 the General Information section "Student Grievance Procedure" in this catalog.

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 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. These advanced courses do not include the basic courses listed under ACM, from ACM 100 to ACM 112.

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 mini-*

mum 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 in Applied Mechanics

Study for the degree of Master of Science in applied mechanics ordinarily will consist of three terms of courses numbered 100 or above totaling at least 138 units. The program must include E 150 abc and one course from among the following: ACM 100, AM 125 abc, ACM 101 abc, or either of the combinations Ma 107, Ma 108 ab, or Ma 107, Ma 109 ab. Note that neither ACM 100 nor either of the combinations involving Ma 107 may be used to fulfill the advanced mathematics requirement for the Ph.D. in applied mechanics. A minimum of 54 units of graduate-level courses must be selected from courses in AM, ACM, Ae, JP, CE, and ME. The 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 in Applied Mechanics

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. The committee member closest to the student's current interests acts as committee chair and interim adviser until this responsibility is assumed by the dissertation supervisor. This committee must meet during the first and third terms of each year of Ph.D. study.

The major professor 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.

Admission to or Continuation in Ph.D. Status. All new students admitted for study toward the Ph.D. degree in applied mechanics, and all other graduate students wishing to become eligible for study toward this degree, are required to take a short oral examination early in the third term of their first year of graduate study at the Institute. This examination, which is conducted by the special joint faculty committee, is confined to elementary topics.

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. If the student chooses to take a subject minor, the units so taken may be included in the total of 108, subject to the approval of 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, Ph 129 abc, or ACM 101 abc or a substitute, acceptable to the faculty in applied mechanics. The requirement in mathematics shall be in addition to the second requirement above and shall not be counted toward a minor.
- Pass the oral candidacy examination. If the student has a minor, an examination on the subject of that program may be included at the request of the discipline offering the minor. The student must take the oral candidacy examination before the end of 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 in Applied Mechanics

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 in Applied Physics
The graduate program in applied physics is regarded by its faculty to be a doctoral program. Students whose goal is the master's degree are admitted rarely, and only in special situations.

A professional in the field should be able to cope with any physics problem that confronts him or her in a technological context. Graduate study in applied physics should therefore cover considerable ground with the least possible loss of depth. Independent and original research is essential, but not for the purpose of acquiring advanced knowledge in a narrow specialty. In today's rapidly changing technology, an applied physicist should not expect to remain precisely within the field of thesis research; the training received should enable him or her to contribute easily to related fields of physics.

Master's Degree in Applied Physics
Of the 135 units required for this degree, at least 54 units must be selected from APh 114, APh 125 or Ph 125, APh 105, Ae/APh 101, and APh 156. Topics in Applied Physics, APh 110 ab, is required. The remaining portion of the 135 units is to be made up from electives approved by the option representative. No more than 27 units may be earned in APh 200.

Suggested electives include APh 105, APh 114, Ae/APh 101, APh 124, APh/EE 130, APh/EE 132, APh 156, APh 183, APh 190, APh 200, APh 125, Ph 129, ACM 101, ACM 104, ACM 105, AM 135, AM 176, ChE 103, ChE 165, Ch 120, Ch 125, Ge 101, Ge 102, Ge 103, Ge 104, and Ge 260. As a result of consultation with his or her adviser, a student may be required to take ACM 100, depending on his or her previous experience.

Degree of Doctor of Philosophy in Applied Physics
Candidacy. To be recommended for candidacy for the doctor's degree the applicant must satisfy the requirements listed below:

- Competence must be demonstrated in the following subjects, at the levels indicated.
  1. Classical Physics: Mechanics and Electromagnetism
     course level: Ph 106 or APh 106
  2. Quantum Mechanics
     course level: APh 125 or Ph 125
  3. Mathematical Methods
     course level: ACM 101, AM 125, or Ph 129
  4. Statistical Physics and Thermodynamics
     course level: APh 105
  5. Solid-State Physics or Fluid Dynamics or Plasma Physics
     course level: APh 114, Ae/APh 101, or APh 156, or Ph 136

  Competence will be demonstrated in either of two ways. The applicant may complete an appropriate Caltech course with a

grade no lower than C. Alternatively, a student supplying evidence of having done equivalent work elsewhere may demonstrate competence through an oral examination. Separate examinations will be required for each area.

- Oral candidacy examination. The student will prepare a brief presentation on a topic agreed upon by the student and the research adviser for the student's proposed thesis; normally the topic will be the projected research. The candidacy examination will be based upon the student's background in applied physics and its relation to this presentation. The oral examination will be given only after the student has demonstrated competence in the five areas, and must be completed before the close of the student's second year of residence.
- Competence in research must be demonstrated as follows: The student must have a doctoral thesis adviser and must have completed 18 units of research with this adviser no later than the beginning of the student's third year of residence.

The Minor. By its nature, applied physics spans a variety of disciplines, and the major requirements reflect this. A minor is *not* required of students majoring in applied physics. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

Thesis and Final Examination. The candidate is required to take a final oral examination covering his or her doctoral thesis and its significance and 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 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 in Applied Physics

Graduate students electing a subject minor in applied physics must complete 54 units of graduate courses in applied physics. The courses may be selected from any of the applied physics courses with numbers *greater than* 100, excluding APh 110 and APh 200.

The student's proposed program must be approved by the Applied Physics Graduate Studies Committee. The committee will examine the course program to determine which of the following areas of interest in applied physics it includes:

Group A: Ae/APh 101, APh 156

Group B: APh 105, APh 114, APh 183, APh 214, or Ph 136

Group C: APh/EE 130 abc, APh 190

It is recommended that the program include courses from more than one of the above areas.

The Applied Physics Graduate Studies Committee may recommend an oral examination based upon its evaluation of the course program. When the program includes more than one of the above areas of interest, then an oral examination may not be required.

Astronomy

Aims and Scope of the Graduate Program in Astronomy
The primary aim of the graduate astronomy program at Caltech is to prepare students for creative and productive careers in astrophysical research. The astronomy 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 astronomy is required to take the placement examination in physics (see Placement Examinations, page 298) 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 astronomy. If it is not, students will be required to pass the appropriate courses.

Master's Degree in Astronomy
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, Ay 122, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 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 in Astronomy
Astronomy 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 122, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127. The student should take these courses in the first year. Also required are research and reading projects, starting in the second term of the

first academic year. 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. This requirement may be reduced on written approval of the department for students who take substantial numbers of units in Ph 106, Ph 125 or APh 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 astronomy 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 will 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 astronomy, 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 C or better, or by special examination, Ay 121, Ay 122, Ay 123, Ay 124, Ay 125, Ay 126, and Ay 127;
- pass a written examination (see below);
- pass an oral examination (see below);
- complete the physics course requirement (see above);
- satisfy a teaching requirement (at least one term as a GTA—see below);
- fulfill the language requirement (see above); and

- be accepted for thesis research by a member of the faculty, or, by special arrangement, a staff member of the Observatories of the Carnegie Institution of Washington.

The written (preliminary) examination will be given in October of the second year. It will cover material from the required astronomy courses, and will consist of two three-hour papers. The results of the examination will be discussed and decided by the faculty. At the discretion of the faculty, a student who has failed the written exam may be offered a second opportunity, which may involve requirements on retaking courses or a second examination. To continue to candidacy, these requirements must be successfully met by the end of the third term of the second year.

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(s) 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 first 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 Astronomy 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 Astronomy 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 astronomy. 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 121–127; begin physics course requirements. Begin research.

Year 2: October—written exam on Ay 121–127. Research projects; select thesis and adviser. Fulfill teaching requirement. Complete 36 units of physics (54 for theorists); optional advanced astronomy courses. Ay 141.

Year 3: Take oral candidacy exam on thesis before end of first 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 in Astronomy

The program for a subject minor in astronomy must be approved by the department before admission to candidacy. In addition to general Institute requirements, the student must complete satisfactorily, with a grade of C or better, 45 units in advanced courses in astronomy.

Biochemistry and Molecular Biophysics

Aims and Scope of Graduate Study in Biochemistry and Molecular Biophysics

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 protein biochemistry, structural biology, and molecular genetics, in addition to an appropriate depth of knowledge in the field selected for the Ph.D. thesis research.

Admission

The option in biochemistry is open to students with undergraduate degrees in biochemistry, biology, chemistry, biophysics, and related areas. All applicants for admission, including those from foreign countries, are required to submit the verbal, quantitative, and ana-

lytical 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 in Biochemistry and Molecular Biophysics
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 in Biochemistry and Molecular Biophysics
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 topics in structural biochemistry (BMB/Bi/Ch 170), the molecular basis of protein function (BMB 176), and molecular genetics (BMB 178). These courses will expose the student to contemporary issues in modern biochemistry, and to the tools and methods that are essential for biochemical research. Students are generally expected to conduct a 10–12 week research rotation in three different laboratories during the first year. Research advisers are normally selected at the end of the first year. In consultation with their adviser and the Option Graduate Study Committee, students are expected to take three advanced courses in the second year 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. 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.

Biology

Aims and Scope of Graduate Study in Biology

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.

Advising and Thesis Supervision
An advisory committee will be constituted for each student, to provide consultation and advice throughout the period of study until admission to candidacy. Each advisory committee will consist of four faculty members, including a student's current research supervisor. The chair is a faculty member other than the research supervisor. The composition of the committee will be adjusted as necessary if the student changes research supervisors or areas of interest. Each student meets with his or her advisory committee at the time of beginning work in the division, to formulate a plan of study; and at other times when problems arise or advice is needed.

The major professor 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.

Teaching Requirements for Graduate Students
All students must acquire teaching experience.

Laboratory Rotations
Prior to choosing a laboratory or laboratories in which to pursue doctoral research, students rotate in two or more laboratories. These rotations serve to expose students to different research problems, strategies, and styles, as well as the facilities available in other laboratories.

BioLunch
Students present their research every other year at BioLunch, a weekly seminar for biological science researchers at Caltech. This seminar—along with the almost daily research seminars by visiting scientists, and at laboratory group meetings, during seminar courses, and presentations at national and international scientific meet-

ings—provides students an opportunity to develop a sophisticated understanding of biological research and to hone communication skills.

Master's Degree in Biology

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 abc.

Degree of Doctor of Philosophy in Biology

Major Subjects of Specialization. A student may pursue major work leading to the doctoral degree in any of the following subjects:

Biotechnology
Cellular Biology and Biophysics
Cellular and Molecular Neurobiology
Developmental Biology
Genetics
Immunology
Integrative Neurobiology
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.

Coursework. A one-year course (Bi 250 abc) covering the breadth of fields represented in biology at Caltech is required of all biology graduate students.

Dual Major in Biotechnology. Students who wish their Ph.D. education to emphasize the development of new techniques and instruments for studying fundamental problems of biology may elect a dual major, combining biotechnology with one of the major subjects of specialization listed in the preceding paragraph. A significant component of the thesis research will be the development of an innovative technique, method of analysis, or instrument. It will also include application of the new technology to a significant biological problem. In preparation for this research, studies in biotechnology may involve significant work outside of biology, in fields such as computer science, chemistry, engineering, and applied mathematics.

Admission to Candidacy. To be recommended by the Division of Biology for admission to candidacy for the doctor's degree, the student must have demonstrated the ability to carry out original research and have passed, with a grade of B or better, the candida-

cy examination in the major subject and one or two minor subjects from the list of major subjects of specialization. Students with a dual major in biotechnology must pass the candidacy examination in the major subject (omitting the normal minor subject or subjects), and a second examination covering knowledge fundamental to the particular work in biotechnology that is proposed by the student. In addition, all students will be expected to make an oral defense to their thesis advisory committee of a written research proposal, on the topic of their anticipated thesis project. This defense will occur 6 to 9 months following passage of the candidacy examination.

Thesis Committee. Before admission to candidacy, a thesis advisory committee is appointed for each student by the chair of the division upon consultation with the student and the major professor. This committee will consist of the student's major professor as chair and four other appropriate members of the faculty. The thesis committee will meet with the student before admission to candidacy to certify that the student has demonstrated the ability to carry out independent research, and at regular intervals thereafter to review the progress of the thesis program. This committee will, with the approval of the dean of graduate studies, also serve as the thesis examination committee (see below).

Thesis and Final Examination. Two weeks after copies of the thesis are provided to the examination 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, to allow as much time as necessary for such matters as public announcement of the examination in the Institute calendar, thesis correction, preparation of publications, and checking out and ordering of the student's laboratory space. 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.

Additional Interdisciplinary Opportunities. A number of emerging fields stem from highly interdisciplinary areas of research, and students interested in biotechnology, geobiology, and computational molecular and cell biology will find additional graduate opportunities within graduate options including biochemistry and molecular biophysics, chemistry, chemical engineering, environmental engineering, computer science, computation and neural systems, and geological and planetary sciences.

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 director of the UCLA MSTP is Professor Stanley Korenman, and Caltech Professor Paul H. Patterson is the associate director. For more information, see http://www.medsch.ucla.edu/mstp/.

Caltech-USC MD/PhD Program

A joint program between Caltech and the USC (Keck) Medical School has been established for the granting of the M.D./Ph.D. degree. Students do their preclinical and clinical work at USC, and their Ph.D. work with any member of the Caltech faculty.

Admission to this joint program is made through the usual USC process, checking a box indicating interest in the Caltech option. 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. Stephen Ryan and Caltech Professor Paul H. Patterson is the Associate Director. For more information, see http://www.usc.edu/schools/medicine/education/MDPhD_Program/.

Minor in Biology

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 Graduate Study in Chemical Engineering
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 the Division of Chemistry and Chemical Engineering will have studied mathematics, physics, and chemistry to the extent that these subjects are covered in the required undergraduate courses at Caltech. In case the applicant's training is not equivalent, the option may prescribe additional work in these subjects before recommending him or her as a candidate.

Master's Degree in Chemical Engineering
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 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 additional 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 in Chemical Engineering
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 oral 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 164, ChE 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 graduate studies brochure of the option. 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 courses specifically excluded are ACM 100 and research in

another option. A grade of C or better is required in any course. 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.

Thesis and Final Examination. See pages 224–225 for regulations concerning theses and final examinations. 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 in Chemical Engineering

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 164, ChE 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. They 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 bulletin "Graduate Programs in Chemical Engineering," distributed annually to first-year chemical engineering graduate students.

Chemistry

Aims and Scope of Graduate Study in Chemistry

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 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 36 units of course work in science or engineering. These 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. Course work outside the scientific area in which the dissertation research is performed is encouraged. 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 in Chemistry

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 in Chemistry

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 Institute 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 Institute Graduate Office.

Subject Minor in Chemistry
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

Aims and Scope of Graduate Study in Civil Engineering
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. 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 of civil engineering, as well as courses in his or her specialty. Most graduate students are also required to take further work in engineering mathematics.

Master's Degree in Civil Engineering
Although the first year of graduate study involves specialized engineering subjects, the student working for the Master of Science degree is encouraged not to overspecialize in one particular field of civil engineering. 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 108 units (minimum) of graduate-level courses from at least three of the five general subject areas of structures and solid mechanics, engineering seismology and soil mechanics, hydraulics and water resources, environmental engineering science, and mathematics.

Students who have not had ACM 100 abc or its equivalent will be required to include ACM 100 in their program. The program must be approved by the student's adviser and the option representative for civil engineering.

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 in Civil Engineering

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. The committee member closest to the student's current interests acts as committee chair and interim adviser until this responsibility is assumed by the dissertation supervisor. This committee must meet during the first and third terms of each year of Ph.D. study.

The major professor 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.

Admission to or Continuation in Ph.D. Status. All new students admitted for study toward the Ph.D. degree in civil engineering, and other graduate students wishing to become eligible for study toward this degree, are required to take a short oral examination early in the third term of their first year of graduate study at the Institute. This examination, which is conducted by the special joint faculty committee, is confined to elementary topics.

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. Students are expected to take not less than 45 units of work in technical subjects, other than the required mathematics, not closely related to their thesis research. If a student chooses to take a subject minor, the units so taken may be included in the total of 108, subject to the approval of the faculty in civil engineering.
- Pass an additional 27 units of course work in advanced mathematics, such as AM 125, ACM 101, Ph 129, or a substitute acceptable to the faculty in civil engineering. For a student whose program is more closely related to the sciences of biology or chemistry than physics, ACM 104 and ACM 105 (or ACM 104 and ACM 181 ab) will be an acceptable substitute for the mathematics requirement.
- Pass the oral candidacy examination. If the student has a subject minor, examination on the minor subject may be included at the request of the discipline offering the minor. The student must take the oral candidacy examination before the end of 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 in Civil Engineering
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. The student must pass an oral examination that is separate from the examination in the student's major.

Computation and Neural Systems

Aims and Scope of Graduate Study in Computation and Neural Systems
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 Physics, Mathematics and Astronomy. This curriculum is designed to promote a broad knowledge of relevant and related aspects of experimental and theoretical molecular, cellular, neural,

and systems biology; computational devices; information theory; emergent or collective systems; modeling; and complex systems; 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, 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 Committees
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. Further meetings with this committee should be arranged as needed by the student or by an adviser. The CNS faculty are available to students during the year for formal and/or informal discussions.

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 spends three 12-week laboratory rotations (one per term) during the first year, and is encouraged to 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.

First-Year Course Requirements
Six nine-unit courses are required during the first year: CNS 187, Bi 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 186, CNS 187, CNS 182, Bi 150, Bi 161, and CNS 156 satisfies this requirement). 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
The three faculty in whose labs rotations have been done are 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 (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 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 six 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 during the first term of year three. (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.

Computer Science

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. Students entering the graduate program with an M.S. degree from another school may transfer credit for course work as appropriate, but must complete the Caltech M.S. requirements, including the M.S. thesis.

The Ph.D. program requires a minimum of three academic years of residence. The first two years are typically devoted to course work and M.S. thesis research as preliminaries to the candidacy examination and Ph.D. thesis research.

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.

Master's Degree in Computer Science

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).
- *Advanced courses in computer science.* Completion of a minimum of 54 units of advanced CS courses in addition to units earned for reading, research, projects, and the M.S. thesis. The student's adviser will assure that this course work represents a balance between theoretical/experimental and hardware/software courses.
- *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.
- *B.S. equivalent preparation.* As an assurance of reasonable breadth in a student's preparation, M.S. students must demonstrate competence in at least four of the five following areas: (a) theory, (b) hardware, (c) systems, (d) software, or (e) applications. Competence can be demonstrated by completion of a corresponding course at Caltech or by undergraduate preparation.
- *M.S. thesis.* Completion of a minimum of 45 units of CS 180, an M.S. thesis approved by a computer science faculty member, signature of a designated computer science faculty member on the M.S. candidacy form, and 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.

Unless a student is exceptionally well prepared, it normally requires several years to complete the course requirements, imple-

mentation experience, and the necessary thesis research required for an M.S. degree in computer science.

Degree of Doctor of Philosophy in Computer Science
The M.S. requirements are part of the Ph.D. requirements.

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 on general knowledge of computer science.

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. This thesis examination is a defense of the thesis research and a test of the candidate's knowledge in his or her specialized fields of research.

Advising and Thesis Supervision. Upon admission each student works directly within a research group and with a designated research adviser. A course of study is determined in consultation with the research adviser. In the second quarter of the first year, all incoming students take a breadth exam, which is administered by the faculty. Its purpose is to ensure that students are adequately prepared to work effectively in their research area.

Throughout their time at Caltech, students meet regularly with their research adviser and are encouraged to also meet with other members of the faculty to guide their progress toward successful completion of the program. As an additional resource, the option representative and executive officer are available to discuss any issues regarding academic progress.

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 Graduate Study in Control and Dynamical Systems
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 in Control and Dynamical Systems
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 in Control and Dynamical Systems
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 required courses CDS 140, CDS 201, CDS 202.
- 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 fluids, vehicles, vibrations, transport phenomena, process design, analog VLSI, propulsion, robotics, turbomachines, power electronics, micromachines, economics, and neurobiology. 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 dynamical systems and/or mathematics.
- Prepare a Research Progress Report.

- Pass an oral examination on the major subject. The oral examination must be 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 in Control and Dynamical Systems
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 Graduate Study in Electrical Engineering
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 in Electrical Engineering
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 are required as approved by the electrical engineering graduate student adviser. Units toward this are not transferable from other schools. At least 54 units of EE courses (courses listed or cross-listed as EE) labeled 100 or above and not counting EE 191 or EE 291 are required. Engineering Seminar, E 150 abc, is required. Students are urged to consider including a humanities course in the remaining free electives.

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 in Electrical Engineering
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 27 units of Pass/Fail grade 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 in Electrical Engineering
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 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. At least 27 units should be in courses over the 100 level. Freshman classes like EE 1 and EE 4 cannot be counted toward this.

Engineering Science/Bioengineering

Aims and Scope of Graduate Study in Engineering Science/Bioengineering
The engineering science/bioengineering option at Caltech is designed for students interested in subjects that form the core of new "interdisciplinary" sciences such as bioengineering. These branches of science provide the basis for the growth of modern technology. Students may choose biology, chemistry, physics, and applied mathematics as their minor subjects and choose a thesis adviser within the Division of Engineering and Applied Science.
Master's Degree in Engineering Science/Bioengineering
One of the following courses in mathematics is required: ACM 101 abc, Methods of Applied and Computational Mathematics I; AM 125 abc, Engineering Mathematical Principles; or Ph 129 abc, Mathematical Methods of Physics.

A minimum of 54 units of courses must have the approval of the student's adviser and the faculty in engineering science.

Degree of Doctor of Philosophy in Engineering Science/Bioengineering
Admission to Candidacy. To be recommended for candidacy for the Ph.D. degree in engineering science, the student must, in addition to meeting the general Institute requirements, do the following:

- Complete 12 units of research.
- Complete at least 50 units of advanced courses arranged by the student in conference with his or her adviser and approved by the faculty in engineering science.
- Pass with a grade of at least C an advanced course in mathematics or applied mathematics such as AM 125 abc, Ph 129 abc, or ACM 101 abc, acceptable to the faculty in engineering science. This requirement shall be in addition to the previous requirement, and shall not be counted toward any minor requirements.

- Pass an oral candidacy examination on the major subject; if the student has a subject minor, examination on the minor subject may be included at the request of the discipline offering the minor.

Language Requirements. Students are encouraged to discuss with their advisers the desirability of taking foreign languages. Foreign languages are not required.

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 in Engineering Science/Bioengineering
A subject minor is not required for the Ph.D. degree in engineering science; however, students majoring in other fields may take a subject minor in engineering science, provided the program consists of 45 units sufficiently far removed from their major program of study and is approved by the appropriate faculty group and by the option representative.

Environmental Engineering Science

Aims and Scope of Graduate Study in Environmental Engineering Science
Environmental problems cut across many disciplines. Graduate study in environmental engineering science emphasizes environmental problem areas and the application of knowledge from several fields of science and engineering to achieving solutions. Opportunities for interactions between several branches of engineering, science, and social science are numerous.

In selecting courses and research topics, each student is advised to plan for both breadth of study of the environment and depth of understanding in a particular subject area. The curriculum has been developed primarily for students pursuing the Ph.D. degree. The purpose of the Ph.D. program is to prepare students for careers in specialized research, advanced engineering, and management in various aspects of the environment. The M.S. degree is also offered for students who plan careers in engineering or in management in some aspect of environmental engineering. Although all graduate students are encouraged to develop an awareness of the wide range of environmental problems, the environmental engineering science program is not designed to train environmental generalists.

Admission
Students with a bachelor's degree in engineering, science, or mathematics may apply for admission to work for either the M.S. or Ph.D. degree, although the program is oriented toward the Ph.D.

degree. Programs of study are arranged individually by each student in consultation with a faculty adviser. In some instances a student may need to take additional undergraduate courses in preparation for graduate work in this field.

Master's Degree in Environmental Engineering Science
For the M.S. degree a minimum of 135 units of work in advanced courses is required. Each student selects a program with the approval of a faculty adviser and the option representative. The program should be well balanced, with courses in several areas of concentration to avoid narrow specialization.

The M.S. program must include three units of Env 150 abc (seminar) and at least 105 units of graduate-level courses from at least three of the following five subject areas (with a minimum of 18 units in each selected area):

- Atmospheric sciences
- Aquatic sciences
- Applied and environmental biology
- Fluid mechanics and transport
- Applied mathematics

At least 63 units must be in Env courses (including joint-listed courses but excluding reading and research units under Env 100 and 300). Students who have not had ACM 100 abc or its equivalent are required to include ACM 100 abc as part of the applied mathematics group. Students are encouraged to take social science and humanities courses as all or part of the 27 elective units included in the total of 135 units.

Suggested courses in the various areas are

- *Atmospheric sciences:* Env 116, ChE/Env 157, ChE/Env 158, ChE/Env 159, Env/Ge 148 ab, Env/Ge/Ch 171, Env/Ge/Ch 172
- *Aquatic sciences:* Env 142 ab, Env 143, Env 146, Env/Ch/Ge 175 ab, Env 216, Bi/Ch 110 abc, Bi/Ch 132, ChE 101, ChE 151 c, ChE/Ch 164, ChE 165, Ch 117, Ch 118 ab, Ge 104, Ge 140 a, Env/Ge 152 a, Ge/Env 149
- *Applied and environmental biology:* Env/Bi 166, Env/Bi 168, Env 208, Env 210, Bi/Ch 110 abc, Bi 122, Bi 180, ChE 163
- *Fluid mechanics and transport:* Env 112 abc, Env 214 abc, Env 216, CE/ME 101 abc, CE 113 ab, CE 210 ab, CE 212, CE 213, ChE 103 abc, ChE 151 ab, Ge 152 ac
- *Applied mathematics:* ACM 101 abc, ACM 104, ACM 105 ab, ACM 181 ab, ACM 100 abc, AM 125 abc, Ma 112 a.
- *Social science:* Ec 118, Ec 122, SS 222 abc

If a student has already earned a master's degree at another university, he or she may not enroll for a master's degree in environmental engineering science unless the previous field of study was significantly different.

If a Ph.D. student completes all the requirements for the M.S. degree as part of the Ph.D. program and does not already have an M.S. degree in this field (or a closely related field), he or she will be awarded the M.S. degree if an M.S. candidacy form is submitted to the option representative.

Degree of Doctor of Philosophy in Environmental Engineering Science
Upon a student's admission to work toward the Ph.D. degree in environmental engineering science, a faculty adviser is appointed to assist in the design of an academic program. The student chooses a thesis adviser at a time when his or her major research interest has become clearly defined, usually before the end of the first year at Caltech. The thesis adviser will act as chair of the three-member counseling committee appointed for each student.

The program of courses for the Ph.D. should be designed to meet the student's need in preparation for research, to provide depth in the major area, and to give breadth of outlook. Each Ph.D. program must receive the approval of the environmental engineering science faculty, upon the recommendation of the faculty adviser and the counseling committee. Students should submit their proposed schedules of courses for the Ph.D. to the faculty for approval as soon as a research area has been chosen.

Areas of Specialization. Students may undertake thesis research in the following areas: air pollution, aerosol physics and chemistry, atmospheric sciences, aquatic sciences, applied microbiology, environmental fluid mechanics, and coastal engineering.

Admission to Candidacy. To be recommended for admission to candidacy for the Ph.D. degree in environmental engineering science, the student must, in addition to meeting the general Institute requirements,

- complete most of the program of courses as arranged in consultation with the advisory committee, to satisfy the guide lines described below, and as approved by the faculty of environmental engineering science;
- pass the oral candidacy examinations.

Major Course Requirements. The major program should be tailored to meet the student's needs in preparation for research and yet provide some breadth as well as depth. For breadth the student must take course work in at least two of the following four areas: air quality; water quality; applied and environmental biology; and fluid mechanics and transport. Major courses will normally be selected from the lists given above for the M.S. degree, although other suitable courses may be proposed.

Mathematics Requirement. Each student must pass at least 27 units of graduate courses in mathematics selected from ACM 101 abc, ACM 104, ACM 105 ab, ACM 181 abc, ACM 100 abc, AM 125 abc, Ph 129 abc, Ma 112 a, or a satisfactory substitute.

Additional advanced mathematics courses will be required as appropriate for each student's area of research on a case-by-case basis as approved by the EES faculty.

Breadth Requirement. Students are expected to take a minimum of 36 units of work in technical subjects, other than the required mathematics, that are not closely related to their thesis research. These courses may, but do not need to, constitute a subject minor in a division other than Engineering and Applied Science or in another program within this division if that program is sufficiently different from EES. Courses in oceanography may be taken at the Scripps Institution of Oceanography under the exchange arrangement described on page 218. In this case, a professor from SIO will be invited to be a member of the committee for either the candidacy examination (part A) or the final examination, or both. Reading courses, seminars, and research units may not be counted toward this requirement.

Minimum Number of Units. The minimum number of units of graduate work is 135, including the courses that satisfy the major, breadth, and advanced mathematics requirement, but excluding research units. Students must pass a minimum of 27 units of advanced mathematics in addition to 108 units of graduate course work in EES and related disciplines. The decision as to the actual total number of math courses needed beyond the minimum requirement for a particular student rests with the student's adviser, advisory committee, and the EES faculty. If students have taken substantial graduate course work at other institutions, the EES faculty may allow a reduced unit total of Caltech courses.

Candidacy Examinations. The candidacy examinations consist of two parts. Part A must be passed *before* registration day of the *spring* quarter of the *second* year of graduate study; however, for students entering with an M.S. (or equivalent), the time limit is June 30 following the *first* year of their graduate study at Caltech. Part A of the examination will test the student on course work and general knowledge of the field.

Part B of the examination must be passed *before* registration day of the *winter* quarter of the *third* year of graduate study; however, for students entering with an M.S. (or equivalent), the time limit is registration day of the *spring* quarter of the *second* year of their graduate study at Caltech. The examination will comprise a critical discussion of a brief written research report provided by the student to the examining committee at least 10 days before the examination. The report will describe accomplishments to date and plans for future research.

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 covers principally the work of the thesis and, according to Institute regulations, must be held at least two weeks before the degree is conferred. Three

copies of the thesis are required of the graduate, one of which is deposited in the Institute library, one in the departmental library, and one with University Microfilms.

Subject Minor in Environmental Engineering Science
A doctoral student in another major field who wishes to take a subject minor in environmental engineering science should submit a proposed minor program to the option representative for approval. The proposed program must consist of 45 or more units in Env courses. Upon completion of these courses the student must pass an oral examination.

Geological and Planetary Sciences

Aims and Scope of Graduate Study
Graduate students in the Division of Geological and Planetary Sciences enter with very diverse undergraduate preparation—majors in astronomy, biology, chemistry, mathematics, and physics, as well as in geochemistry, geology, and geophysics. Graduate study and research within the division are equally diverse, and the graduate program aims to provide for students a depth of competence and experience in their major field, sufficient strength in the basic sciences to allow them to continue self-education after their formal training has been completed, and the motivation and training to keep them in the forefront of their field through a long and productive career. Students are encouraged to explore work in interdisciplinary areas both within and outside the division, and to gain experience in teaching. Although financial support is not guaranteed, all students making normal progress have in the past been supported by a combination of fellowships, research assistantships, and teaching assistantships.

Admissions 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 aptitude tests. The advanced test in their field of undergraduate specialty is optional. 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. 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 and discuss their preparation in the basic sciences. Afterward, the student meets with his or her adviser prior to registration and selects courses based in part on the results of the discussions.

Students are encouraged to register for at least nine units of research (Ge 297) in each of two out of the first three terms of residence. Each of these terms of research should be under the direction of different faculty members. 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 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 Advisory Committee evolves into the Thesis Examining 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, 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 101, 102, 103, 108, and 109.

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 administered by the qualifying examination committee, which has members from the four options of the division, and is normally taken early in the first term of the second year of residence. A more detailed outline of the qualifying examination is available in the division Academic Affairs office.

Before the end of the second year, the Thesis Advisory Committee will be selected, as outlined above.

The basic divisional course requirement includes 47 units within the division but outside the area of the student's option. The required 47 units of courses outside the major field may be used to satisfy a subject minor in another option of the division. Every graduate student in the division is responsible for the basic general information covered in the four courses Ge 101, 102, 103, and 108, and the courses should be completed during the first year. Students are required to take the two courses in Ge 101, 102, and 103 that are outside their option. Academic advisers may recommend that students with insufficient training in their major field take the appropriate course in addition. Students may petition instructors to drop one of the two courses if they already have substantial academic training in that field; approval of their academic adviser or option representative is required. Students may be excused from Ge 108 by petition to their academic adviser if they can demonstrate that they already have equivalent training and understanding of the mathematics and physics covered in Ge 108. Oral presentation, Ge 109, is required of all degree candidates and counts for three of the units listed above. Throughout their graduate careers, students are expected to attend departmental seminars and seminar courses led by visiting scientists. Students may submit a petition to their option to substitute appropriate graduate courses taken at other institutions, corresponding to no more than 27 units.

The division encourages students to engage in research early in their graduate careers. A student making normal progress will have submitted a paper, of which the student is senior author, by the end of the third academic year. The paper will be submitted to a

refereed scientific journal and must have the approval of 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. A manuscript should be reviewed by the member of the faculty supervising the major research and should be ready for submission to a refereed scientific journal at the time of the final exam. The student should be principal author. The published paper should have a California Institute of Technology address and a Division of Geological and Planetary Sciences contribution number, and at least five reprints should be sent to the division. Published papers may be included in the thesis.

By the end of 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 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 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.

End of 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.

Requirements of the Major Subject Options

Geology and Geobiology. In addition to the general Institute and basic division requirements, which include taking at least 47 units within the division in subjects other than their own major subject, candidates for the Ph.D. in geology or geobiology must successful-

ly complete a minimum of 90 units of 100- to 200-level courses, including the advanced courses most pertinent to their major field. Courses that cannot be used to satisfy these requirements include languages, research and reading courses, and certain courses constituting basic preparation in their field, as follows: Ge 106, Ge 114, and Ge 115. At least 36 of the 90 units must be taken outside the Division of Geological and Planetary Sciences (with a grade of C or better). It is possible for these to be used to satisfy part of the requirements of a minor. Also, Ch 21 abc may be included as part of these units. Knowledge of field geology equivalent to Ge 121 ab is required of all majors. For good work in most modern earth science fields, a proficiency in mathematics is essential.

Geochemistry. In addition to general Institute and basic division requirements, the candidate for a Ph.D. degree in geochemistry is required to complete 90 additional units of course work at the 100 level or greater. These courses must include 45 units outside the division and include the advanced courses most relevant to the student's thesis research. This option requires all students to have a basic knowledge of chemistry at the level of Ch 21. The 45 units of courses submitted for fulfillment of the basic division requirement must include one quarter of field geology. Reading and research courses may not be used, although students are expected to take such courses and to devote each summer to research.

Students completing the geochemistry academic program are required to submit a tentative proposal for their research no later than May 1 of the third year in residence. This proposal should document the scientific importance of the project relative to previous work, feasibility of completion within an allowable graduate-student tenure, and, if any, preliminary results. The proposals will be reviewed by the geochemistry faculty.

Geophysics. In addition to general Institute and basic division requirements, the Ph.D. candidate in geophysics must successfully complete a minimum of 90 units of 100- to 200-level courses chosen from the two categories below. At least 36 units must be completed from each group. Courses with less than five units per term in these groups will not be accepted.

Group A. Courses in mathematics, applied mathematics, physics, applied physics, and chemical physics. A minimum proficiency in basic mathematical methods at the level of ACM 101 and in basic physics at the level of Physics 106 is required.

Group B. Courses in geophysics.

Students with an exceptionally strong background in one or more of the areas represented by these groups may, upon petition to the option representative, be excused from up to 18 units of the overall 90-unit requirement. Research and reading courses cannot be used to satisfy these requirements but are highly recommended as preparation for the oral qualifying examination.

Planetary Science. In addition to general Institute and basic division requirements, the candidate for a Ph.D. degree in planetary science shall acquire at least a minimum graduate background in each of three categories of course work: (1) the earth sciences, (2) physics, mathematics, chemistry, and astronomy, and (3) planetary science, which shall include at least one quarter in Planetary Atmospheres (Ge 152 a, or b, or c) and one quarter in Planetary Surfaces (Ge 151). These requirements may be met by successful completion (normally B average or higher) of at least 45 units of suitable course work at the 100 level or higher in each category. The requirements in the first category coincide with the basic division requirement. Reading and research courses may not be used, although students are expected to take such courses and to devote each summer to research in planetary science. Planetary Science Seminar (Ge 225 abc) is required each year for all planetary science students.

Students shall demonstrate professional competence in a second scientific field distinct from their specialization within planetary science. This may be accomplished by satisfactory completion of a subject minor. Courses used to satisfy this secondary requirement may also be used to satisfy the requirements in one of the 45-unit categories.

Minor in Geological and Planetary Sciences
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.

Materials Science

Aims and Scope of Graduate Study in Materials Science
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. 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 in Materials Science

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: Structure and Bonding in Materials, Diffraction and Structure of Materials, Kinetic Processes in Materials.
2. APh 105 a or ChE 165, APh 105 b or ChE/Ch 164, MS 105: Thermodynamics, Statistical Mechanics, Phase Transformations.
3. Two quarters of courses focused on specific materials, such as APh 114 ab: Solid State Physics; Ch/ChE 147, ChE/Ch 148: Polymer Synthesis and Physics; Ge 114, Ge 214, Ge 260: Mineralogy, Spectroscopy of Minerals, Physics of Earth Materials.
4. Two quarters of courses focused on internal interactions in materials, such as Ph 125 ab, Ch 125 ab: Quantum Mechanics; AM 135 ab: Mathematical Elasticity Theory; Ch 120 b: Nature of the Chemical Bond; Ch 121 ab: Materials and Molecular Simulations.
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 124, MS 125, and APh/MS 141.
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 ab (2 units) or E 150 abc (3 units), seminar.

Degree of Doctor of Philosophy in Materials Science

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 Four 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 in Materials Science
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 Graduate Study in Mathematics
The principal aim of the graduate program is to equip the student to do original research in mathematics. Independent and critical thinking is encouraged by participation in seminars and by direct contact with faculty members; an indication of the current research interests of the faculty is found on page 103. In order to enable each student to acquire a broad background in mathematics, individual programs of study and courses are mapped out in consultation with faculty advisers. The normal course of study leads to the Ph.D. degree.

Admission
Each new graduate student admitted to work for an advanced degree in mathematics will be given an interview on Thursday or Friday of the week preceding the beginning of instruction in 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. First-year students are also expected to consult regularly with their faculty mentor (see the section on advising). The work of the student during the first year will include independent reading and/or research.

Course Program
The graduate courses offered, listed in Section Five, are divided into three categories. The courses numbered between 100 and 199 are basic graduate courses open to all graduate students. The three core courses at the graduate level—Ma 110 in Analysis, Ma 120 in Algebra, and Ma 151 in Geometry and Topology—are required of all graduate students unless waived by the Graduate Committee. Normally students are expected to complete these core courses in the first year and to take additional advanced courses while doing their thesis research. In addition to the core courses, students are required to complete nine quarters of other advanced mathematics courses, of which at least two quarters must be in the area of discrete mathematics: combinatorics, logic, complexity, and computability. Under special circumstances (e.g., finishing the degree in three years), exceptions to these requirements may be granted by the graduate option representative.

The courses in the second category are numbered between 200 and 290. They are taken normally by second-year and more advanced graduate students. They are usually given in alternate years. The 300 series includes the more specialized courses, the research courses, and the seminars. They are given on an irregular basis depending on demand and interest.

Each student must participate actively in seminars for a total of at least three terms. Students are strongly encouraged to do this within the first two years of graduate studies, but must complete this before advancement to candidacy. The department will help to make seminars accessible to students. Guidelines will be distributed to the students at the beginning of each academic year.

Beginning with the second year at the latest, the student will be expected to begin independent research work and will be strongly encouraged to participate in seminars.

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.

Master's Degree in Mathematics

Entering graduate students are normally admitted directly to the Ph.D. program, since the Institute does not offer a regular program in mathematics leading to the master's degree. This degree may be awarded in exceptional circumstances either as a terminal degree or as a degree preliminary to the Ph.D. degree. 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 at the Institute 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 in Mathematics

Advising and Thesis Supervision. Each entering student is assigned a faculty mentor who will advise the student on course selection in the first year and will play a continuing role complementary to that of the thesis adviser throughout the student's graduate career. In particular, the mentor will guide the student's development of teaching and communication skills, which the faculty regard as critical components of a mathematician's education.

Normally by the beginning of the second year (and in any case before the candidacy examination), students are expected to have a thesis adviser, a member of the faculty who has agreed to supervise their research.

Students receive help and advice not only from their thesis adviser and faculty mentor, but also whenever needed from the graduate option representative, the executive officer, and the faculty ombudsperson in mathematics. (See also the section Guidelines for the Graduate Student–Faculty Adviser Relationship on page 218.)

Candidacy Examination. Before being admitted to candidacy for the Ph.D. in mathematics, the student is expected to have acquired an understanding of the main fields of modern mathematics and to have demonstrated an ability to do competent research in a particular field.

The first graduate year is usually spent in acquiring basic background knowledge. In order to determine as early as possible the candidate's progress toward this objective, qualifying examinations will be given toward the end of the first year of graduate study. Students must take two of three examinations: one covering the field of algebra, one covering real and complex analysis, and one covering geometry and topology. These emphasize the ability to apply basic mathematical ideas and theorems to specific cases. The three core courses should be adequate preparation for these examinations. Before being admitted to candidacy, students must pass two of these three examinations and, in the one not taken, must take and pass the corresponding core course with a grade of B or better.

Sometime before the end of the third year the student must give an oral presentation to a committee of faculty members, which will describe the general subject matter of the proposed area of thesis research and describe the tentative thesis problem. These descriptions must also be presented to the committee in written form (typically 3–10 pages) at least one week before the oral examination. The committee will consist of three members, including the student's adviser. It is the student's responsibility to arrange the formation of this committee in consultation with the adviser. A satisfactory performance on this oral presentation is required for admission to candidacy.

During the summer following the first year of graduate work, each graduate student in mathematics is expected to plan a program of independent study and research work under the guidance of some member of the mathematics staff. This summer program should provide the student with an opportunity to acquire new mathematical knowledge and to generate new mathematical ideas. Shortly after the beginning of the fall term, the faculty will make an overall evaluation of the progress and research potential of these graduate students. The results of this evaluation will be reported to each student and will be used in consultation with the student to plan a subsequent academic program. At this time each student is expected to arrange for a member of the faculty to act as a research 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 typewritten or reproduced copies of their thesis to their supervisors. These copies must be complete and in the exact form in which they will be presented to the members of the examining committee. Candidates are also responsible for supplying the members of their examining committee, at the same time or shortly thereafter, with reproduced copies of their thesis. The final oral examination on the thesis will be held within three weeks from the date the thesis is handed in.

Subject Minor in Mathematics

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.

Mechanical Engineering

Aims and Scope of Graduate Study in Mechanical Engineering

The aim of the graduate program in mechanical engineering at Caltech is to prepare students for research and professional practice in an era of rapidly advancing interdisciplinary technology. The program combines individual depth of experience and competence in a particular chosen major specialty, 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 engi-

neering 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, pollution control, 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 in Mechanical Engineering

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.

Program Required for Mechanical Engineering

- 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, ME 119 abc, AM 102 abc, AM 151 abc, CDS 110 ab, and CDS 111.
- 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 aerosols and air pollution (Env 116, ChE/Env 158, ChE/Env 159); automation and robotics (ME 115 ab, ME 131, ME 132); combustion (ChE 157, JP 213 abc); engineering design (ME 171); multiphase flows (ME 202 abc); propulsion (JP 121 abc); experimental methods (Ae 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, Env, 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, E 150—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 in Mechanical Engineering
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 initial counseling committee of three faculty members is appointed for each student upon admission to work toward a Ph.D. degree in mechanical engineering. The committee member closest to the student's current interests acts as committee chair and interim adviser.

The major professor 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.

Ph.D. Dissertation Supervision Committee. It is the responsibility of the student to find a research adviser. In consultation with the adviser, the student must form a Ph.D. dissertation supervision committee, which will meet during the first and third terms of each year of Ph.D. study. 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 student's adviser shall serve as chair of this committee.

Admission to or Continuation in Ph.D. Status. All new students admitted for study toward the Ph.D. degree in mechanical engineering, and all other graduate students wishing to become eligible for study toward this degree, are required to take the preliminary oral examination early in the third term of their first and third years of graduate study at the Institute.

Admission to Candidacy for the Ph.D. in Mechanical Engineering. 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.
- Successfully complete at least 54 units of research and demonstrate satisfactory research progress.

- Pass with a grade of at least C a minimum of 27 units of course work in each of three of the core areas of mechanical engineering listed below. Examples of suitable courses are given in parentheses.
  Fluid Mechanics (Ae/APh/CE/ME 101 abc)
  Thermo/Heat Transfer (ME 119 abc)
  Solid Mechanics (AM 102 abc)
  Dynamics and Vibrations (AM 151 abc)
  Mechanical Systems and Design (ME 115 ab, ME 171, ME 175)
  Controls (CDS 110 ab, CDS 111, or CDS 112)
  The student may petition the mechanical engineering faculty to replace one of the areas with an area not listed above. These 81 units may also be used in the student's program for the master's degree.
- Pass with a grade of at least C an additional 27 units in engineering or science (with a course number above 100) which pertain to the student's specialty.
- Pass with a grade of at least C an advanced course in mathematics or applied mathematics (for example, AM 125 abc or ACM 101 abc) that is acceptable to the student's committee and the faculty in mechanical engineering. The requirement in mathematics is in addition to the requirements above and cannot be counted toward a minor.
- Pass 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.

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.

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, 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 in Mechanical Engineering
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 Graduate Study in Physics
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 Dean of Graduate Studies, California Institute of Technology, Pasadena, CA 91125, or can be downloaded from http://www.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.gre.org/).

Placement Examinations
Students admitted to work for an advanced degree in physics are required to take placement examinations, typically given the

Thursday preceding the beginning of instruction of 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 in Physics

A Master of Science degree in physics will be awarded 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 130, Ph 135, Ph 136, Ph 151, Ph 161, Ph 176, 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.

Doctor of Philosophy in Physics

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.

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, which may be taken pass/fail. 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; courses satisfying this requirement can be taken pass/fail. 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. Further information can be found at http://www.pma.caltech.edu/information.html.

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 in Physics

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.

Science, Ethics, and Society/History and Philosophy of Science

Graduate students in science, mathematics, or engineering may take a minor in science, ethics, and society (SES). The minor provides students with a historical and philosophical education in the social, economic, ethical, and political problems that have arisen in the modern world in connection with the advance of science and technology. It provides opportunities for study of the development of science and technology since the Scientific Revolution, and for inquiry into the evolution of ethical and policy issues in areas such as research and development, technological innovation, energy supply and conservation, the environment, and biomedicine. Work in the minor concerns historical and/or philosophical examinations of subjects such as genetics and molecular biology, the birth of modern physics, the politics of research and development, the social uses of biological knowledge, the nature of scientific explanation, and the evolution of theories of cognition; but it may also include consideration of contemporary issues concerning science and technology treated in philosophical, ethical, and historical perspective. The minor thus focuses on the acquisition of broad basic knowledge about persistent issues in the affairs of science, technology, and society so as to enable students to deal with such issues in the future, whatever particular form they may take. It is thus a valuable supplement to a technical degree, since it helps equip students to meet the nontechnical social, economic, and political chal-

lenges that people in technical careers increasingly encounter. Students who successfully complete the SES minor will be recognized with official credit for the achievement on their transcripts.

SES Graduate Minor Requirements
Graduate students who take an SES minor are expected to complete SES 10 ab, SES 102 bc, at least three units of SES 103, and 18 units of additional work in SES. Students need not complete the requirements for the minor within the first two years of graduate study. Students who have completed work in SES subjects equivalent to SES 10 a or SES 10 b before coming to Caltech may be given credit toward the completion of the minor requirements.

Social Science

Aims and Scope of Graduate Study in Social Science
Over the past two decades, it has become ever more apparent that many of the most serious problems faced by the nation have both an economic and a political component. Graduate education, however, has remained largely compartmentalized, with most programs producing students who, while well trained in economics or in political science, are not trained in both. The Caltech Ph.D. program in social science is designed to graduate scholars who are well grounded in the theoretical perspectives, the quantitative techniques, and the experimental methods of economics and of political science and who also have been introduced to quantitative history and to law as well. In addition to providing students with a solid foundation in the underlying disciplines, the program has a substantial policy component that brings institutional design—an analysis that merges work in theory, experimentation, and history—to policy studies in a way that is done at no other institution.

Recent graduates of the program have taken positions in departments of economics, political science, and public policy, and in schools of business at major universities. A smaller number have taken positions as economic analysts, program evaluators, and planners for government or private business. In addition, a special program enables students to obtain joint degrees in social science from Caltech and in law from cooperating professional schools. Graduates of this latter program are qualified for teaching positions in schools of law, for legal practice, and for other positions in academia and government.

Admission
The requirements for admission to the graduate program in social science are in the field of mathematics. Entering students are expected to have completed 1) courses in calculus at the levels of Ma 2 abc; 2) a course in linear algebra; and 3) a course in mathematical statistics. Students who have not completed some of these courses

may be admitted with the understanding that they will complete these mathematical requirements after entering the program. Entering students must provide Graduate Record Examination scores and may be asked to take placement examinations in mathematics to determine their level of achievement. The extent of remedial work, if any, will be determined by the option's director of graduate studies (DGS) in consultation with the student.

Students are also expected to take any additional mathematics courses relevant to their research. For example, research in many areas of social science requires mathematical competence at the level of Ma 108.

Course Program

During the first year of residence, core requirements consist of four three-quarter courses: SS 201 abc (analytical foundations of social science); SS 202 abc (political theory); SS 205 abc (foundations of economics); and SS 222 abc (econometrics). Successful progress during the first three quarters of residency requires that the student complete a minimum of 36 units of work in each quarter with an average grade of B or better, and with no grade less than C. A student is expected to complete these courses by the end of the first year of study. The DGS will review each student's progress at the end of every quarter during the first year and bring deficiencies to the attention of the student and the faculty at large. While these core courses are not required for a degree, the student bears the burden of demonstrating competence in each area and must show that omission from his or her program of one or more of these courses will not impede normal progress toward the degree. A decision to omit a course requires written approval by the DGS and should be made in consultation with the DGS and the relevant faculty.

At the end of the third term (of the first year), all students are required to take the preliminary examination. This written exam is given in three parts and covers the areas of analytical politics, economics, and econometrics. To pass the examination, each student must pass all three parts. A student who fails the examination on the first attempt may retake it a second time, but that attempt must be made before the beginning of the second year. If a student does not pass the examination on the first attempt, he or she may be asked to retake any or all parts. A student whose performance on the second attempt is marginal may be given an oral examination by the faculty to determine if he or she should be passed.

During the second year, each student must complete a minimum of 36 units of regular course work each quarter (again with an average grade of B or better). Of the 108-unit total, a student must successfully complete at least six one-quarter workshops (54 units) and receive at least a grade of B in each. These research-oriented courses are designed to introduce the student to indepen-

dent research, and they require that the student demonstrate his or her ability to pursue a research project successfully. The six workshops should be chosen in consultation with the DGS and those faculty members who are working in the area in which the student wishes to do his or her thesis research. The choice should be made with the long-term research goals of the student in mind. A student should take at least three workshops in the discipline that he or she expects to pursue, with a focus on the specific fields in which he or she will specialize, e.g., applied or theoretical economics or politics, econometrics, or quantitative history; and usually the student should complete two sets of three sequential workshops.

In each year there will usually be workshops in economic theory, applied economics, political theory, and some substantive areas of political science. In addition, although all may not be offered each year, there are also workshops in econometrics, finance, law, quantitative history, and public policy. Thus a student should have ample opportunity to meet the six workshop requirements and to prepare for a future research career. A student should also bear in mind that a major strength of the program is its multidisciplinary nature, and he or she is encouraged to sample a variety of fields. Students and faculty are reminded that independent reading and study courses do not count toward the 36 units per quarter requirement.

Under any conditions, however, each student must complete at least *two* papers, one of which must be solely authored by the student. All required research papers from the six workshops must be finished and submitted to the entire social science faculty no later than the end of the third term of the second year. In addition, the student will be asked to present a solely authored paper in an optionwide colloquium, sometime between April 1 and June 15 of the second year.

Degree of Doctor of Philosophy in Social Science

Candidacy. After the completion of the second-year requirements, the student's overall performance and research potential of the past two years will be evaluated by the social science faculty. If this evaluation is favorable and when an option faculty member has accepted the student for thesis research, the student will be admitted to candidacy for the Ph.D. No later than the beginning of the third year, a student in good standing should be prepared to file candidacy papers with the dean of graduate studies.

Satisfactory progress during the third and fourth years toward completion of the Ph.D. consists of the following.

Organization of Thesis Committee. While the DGS is responsible for each student's general academic welfare throughout the duration of the program, a student should begin organizing his or her thesis committee. A student should select an adviser (that is, a

committee chair) prior to the first quarter of the third year. The adviser must be a member of the social science faculty at Caltech. The choice of an adviser is important since the adviser is the primary judge of a student's progress in research and bears principal responsibility for the quality of that research. The adviser is also charged with the administrative responsibility for organizing the remainder of the committee. Thus a student should select an adviser whose own work is closely related to his or her research interests. It is, however, always possible to change advisers, if the student's research shifts focus. Since general supervision over the direction and progress of the dissertation rests with the adviser, the student should raise with the adviser such matters as the design of the dissertation, the planned content of each portion of the dissertation, or any major changes in the topic. This rule also applies to discussions about the acceptability of completed portions of the dissertation prior to the oral defense. Should other committee members need to be consulted about any of these issues, the adviser is the appropriate party to initiate such a consultation. The student is expected to discuss the substantive content of the dissertation with the remainder of the committee and to keep the committee informed of his or her progress on a regular basis. The student is, of course, free to discuss substantive issues with any member of the faculty.

A second committee member should be chosen by the end of the first quarter of the third year. The second member should be able to evaluate the entire dissertation and vouch for its quality. For that reason, a second committee member should be chosen as soon as possible.

We require that the student submit a dissertation prospectus that outlines briefly the relevant literature, the student's proposed dissertation work, and 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 committee member by the end of the first quarter of the third year, and must be filed with the DGS.

Because of Caltech's unique multidisciplinary program in social science, a student often selects topics that are broader than the specializations of individual faculty members. In such cases, the student is encouraged to select the adviser and the second committee member early in the process of dissertation research, and possibly to choose faculty members from different fields—or even disciplines. The second member must also be a member of the social science faculty. If the student and adviser believe that additional committee member(s) from outside the social science faculty are necessary and appropriate, the student must petition the DGS. The option bears no financial obligation to ensure any outside member's appearance at the thesis defense.

During the third quarter of the third year, and under any conditions at least two quarters before completion of the dissertation, a student, in consultation with his or her adviser, should select a third committee member. This choice should be based on the content of the ongoing dissertation research, and might well be made for the purpose of providing specialized help (perhaps in theory, econometrics, institutions, experimental methods, or history). It is not necessary that the third member be responsible for the full breadth of research covered by the dissertation.

Supervision. At the end of each quarter during the third and fourth years of residence, the thesis adviser and the DGS will meet to determine whether the student is making sufficient progress in research to provide a reasonable expectation of completion within four years. Satisfactory progress will be normally judged by how closely the student has adhered to the schedule given in his or her prospectus, and on the basis of the quality of the research which has been undertaken and evaluated by the thesis committee. It is expected that the student will have completed all requirements for the Ph.D. degree by the end of his or her fourth year of residency.

Before the final oral is scheduled, the division chair will select a fourth committee member who will act as an outside reader. The fourth member may be any faculty member from the option, from some other graduate option at the Institute, or from another university. The option will, of course, assume any financial obligations imposed by the fourth member.

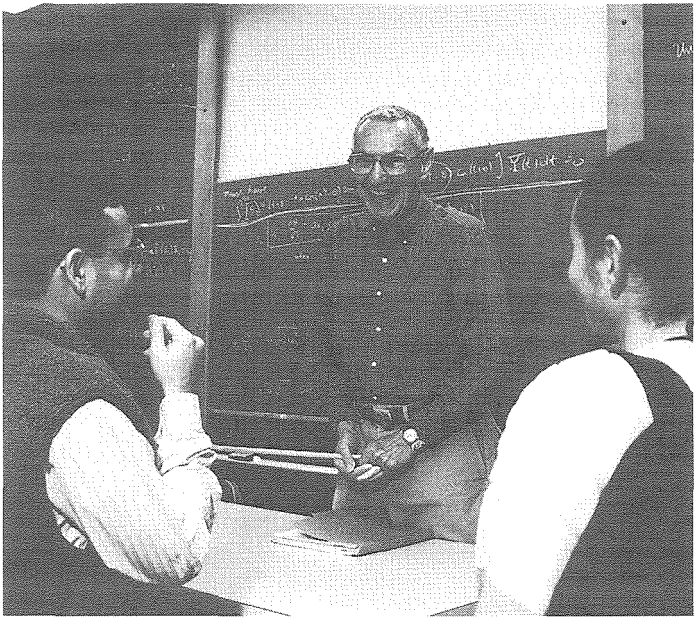
Thesis and Final Examination. When the student is ready to schedule an oral dissertation defense, he or she must provide a written copy of the dissertation to the DGS at least two weeks prior to the planned defense date. The DGS will insure that the thesis meets minimal standards for successful completion of the Ph.D. degree and will also distribute copies to all members of the dissertation committee. In addition to scheduling an oral defense with the members of the dissertation committee, it is expected that the student will present an optionwide colloquium on parts or all of the dissertation research within two weeks of the oral defense.

The dissertation is expected to represent publishable, original research with a coherent theme. To that end, the dissertation should have some unifying principle and descriptive title. Moreover, successful completion implies that the faculty has certified that the candidate is a trained, professionally knowledgeable, and potentially productive scholar in his or her chosen area of work. While exact quantification is impossible, a thesis should represent a major part of a publishable book, or two or three articles that are acceptable to first-rate professional journals.

Master's Degree in Social Science
Entering graduate students are admitted to the Ph.D. program. The M.S. degree is awarded in exceptional cases. Of the 135 units of graduate work required by Institute regulations, at least 81 units should be advanced work in social science. Students petitioning for an M.S. are required to take an examination.

Subject Minor in Social Science
Graduate students taking social science as a subject minor shall complete a program of not less than 45 units in advanced courses in a coherent program of study that has been approved by the DGS.

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 hour.

Abbreviations

Ae	Aeronautics	En	English
An	Anthropology	Env	Environmental Engineering Science
ACM	Applied and Computational Mathematics	Ge	Geological and Planetary Sciences
AM	Applied Mechanics	H	History
APh	Applied Physics	Hum	Humanities
Art	Art History	ISP	Independent Studies Program
Ay	Astronomy	JP	Jet Propulsion
BMB	Biochemistry and Molecular Biophysics	L	Languages
Bi	Biology	Law	Law
BEM	Business Economics and Management	Lit	Literature
		MS	Materials Science
ChE	Chemical Engineering	Ma	Mathematics
Ch	Chemistry	ME	Mechanical Engineering
CE	Civil Engineering	Mu	Music
CNS	Computation and Neural Systems	PA	Performance and Activities
		Pl	Philosophy
CS	Computer Science	PE	Physical Education
CDS	Control and Dynamical Systems	Ph	Physics
		PS	Political Science
Ec	Economics	Psy	Psychology
EE	Electrical Engineering	SES	Science, Ethics, and Society/History and Philosophy of Science
E	Engineering		
ES	Engineering Science/Bioengineering	SS	Social Science

Ae 100. Research in Aeronautics. *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.* 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. Instructor: Colonius.

Ae/AM/CE 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisite: AM 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: Bhattacharya.

Ae/JP 103 abc. Propulsion, Dynamics, and Control of Aircraft. *9 units (3-0-6); first, second, third terms. Prerequisites: ACM 95/100 abc or equivalent (may be taken concurrently); basic knowledge of fluid mechanics; CDS 110 a or equivalent for third term only.* The first half of this course will cover the various types of propulsion systems suitable for flight in the atmosphere, including propellers, gas turbines, and rockets. Basic topics include the mechanics of flow through compressors and turbines; combustion problems for propulsive devices; and flow through nozzles. Emphasis in the second half of the course will be placed on elementary airfoil and wing theory; elementary problems of performance; small amplitude dynamical motions; and stability and control. Most of the third term will be devoted to applications of classical and modern control theory to feedback control of longitudinal and lateral motions of rigid aircraft. Instructor: Culick.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6 first term; 1-3-5 second and third terms). Prerequisites: ACM 95 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: Gharib.

CE/Ae/AM 108 abc. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

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. Instructor: Egolfopoulos.

Ae 125 abc. Spacecraft Systems Engineering. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, Ph 2 ab, Ma 2 ab, AM 35 ab.* Grades only; not offered on a pass/fail basis. This course presents the fundamentals of modern concurrent systems engineering in the context of spacecraft and mission engineering. The basic theory and practical application of the following topics are addressed: concurrent systems engineering principles and methods; spacecraft systems analysis; attitude determination and control; rocket propulsion; space avionics; payload integration; spacecraft mechanical and thermal design; and elementary astrodynamics. Ae 125 a: Spacecraft and mission design problems selected by the instructor. Ae 125 b,c: Spacecraft and mission design studies in which students assume the roles of cognizant engineers. Instructor: Sercel.

Ae 150 abc. Aeronautical Seminar. *1 unit (1-0-0); first, second, third terms.* Speakers from campus and outside research and manufacturing organizations discuss current problems and advances in aeronautics. Graded pass/fail only. Instructor: Shepherd.

Ae/AM 160 abc. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6); first, second, third 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, co-rotational, 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: Rosakis.

Ae 200. Advanced Research in Aeronautics. *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 abc. Advanced Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM 101 (may be taken concurrently).* Foundations of the mechanics of real fluids. Basic concepts will be emphasized. Subjects covered will include a selection from: 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: Pullin.

Ae 204 abc. Technical Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent.* External and internal flow problems, encountered in engineering, for which only empirical methods exist. Turbulent shear flow, separation, transition, three-dimensional and nonsteady effects. Basis of engineering practice in the design of devices such as mixers, ejectors, diffusers, and control valves. Studies of flow-induced oscillations, wind effects on structures, vehicle aerodynamics. Not offered 2000–2001.

Ae 208 abc. Fluid Mechanics Seminar. *1 unit (1-0-0); first, second, third terms.* A seminar course in fluid mechanics. Weekly lectures on current developments are presented by staff members, graduate students, and visiting scientists and engineers. Graded pass/fail only. Instructor: Hornung.

Ae/AM 209 abc. Seminar in Solid Mechanics. *1 unit (1-0-0); first, second, third terms.* A seminar for staff and students of all divisions whose interests lie in the general field of solid mechanics. Reports on current research by staff and students on campus are intermixed with seminars given by invited lecturers from companies and other research institutions. Graded pass/fail only. Instructor: Knauss.

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 213 abc. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/AM/CE 102 abc (concurrently) or equivalent and instructor's permission.* Analytical and experimental techniques in the study of fracture in

metallic and nonmetallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of nontraditional materials. Fatigue crack growth and life prediction techniques will also be discussed. In addition, "dynamic" stress wave dominated, failure initiation growth and arrest phenomena will be covered. This will include traditional dynamic fracture considerations as well as discussions of failure by adiabatic shear localization. Instructor: Ravichandran.

Ae/AM/CE 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 102 abc or equivalent; Ae/AM 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. Spacetime methods. Inelastic solids. Constitutive updates. Stability and convergence. Consistent linearization. Applications to finite deformation viscoplasticity, viscoelasticity, and Lagrangian modeling of fluid flows. Not offered 2000–2001.

Ae/AM 215. Dynamic Behavior of Materials. *9 units (3-0-6); third term. Prerequisites: ACM 100 abc or AM 125 abc; Ae/AM/CE 102 abc or AM 135 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 2000–2001.

AM/Ae 220 ab. Elastic Stability of Structures and Solids. *9 units (3-0-6).* For course description, see Applied Mechanics.

Ae 221. Theory of Viscoelasticity. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE 102 abc or equivalent and instructor's permission.* Material characterization and thermodynamic foundation of the stress-strain laws. Correspondence rule for viscoelastic and associated elastic solutions and integral formulation for quasi-static boundary value problems. Treatment of time-varying boundary conditions such as moving boundaries and moving loads. Stress waves. Approximate methods of viscoelastic stress analysis. Not offered 2000–2001.

Ae/AM 223. Plasticity. *9 units (3-0-6); first term. Prerequisite: Ae/AM/CE 102 abc or instructor's permission.* Theory of dislocations in crystalline media. Characteristics of dislocations and their influence on the mechanical behavior in various crystal structures. Application of dislocation theory to single and polycrystal plasticity. Theory of the inelastic behavior of materials with negligible time effects. Experimental background for metals and fundamental postulates for plastic stress-strain relations. Variational principles for incremental elastic-plastic problems, uniqueness. Upper and lower bound theorems of limit analysis and shakedown. Slip line theory and applications. Additional topics may include soils, creep and rate-sensitive effects in metals, the thermodynamics of plastic deformation, and experimental methods in plasticity. Instructor: Suguet.

Ae/AM 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. Instructors: Suguet, Ortiz.

Ae/ACM 232 abc. Computational Fluid Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; ACM 100 abc or AM 125 abc or equivalent; ACM 104, ACM 105 ab or equivalent.* Introduction to the use of numerical methods in the solution of fluid mechanics problems. First term: Problem-oriented review of numerical methods for inviscid and viscous incompressible flows. Vortex methods in two and three dimensions. Vortex merging and roll-up. Free shear layers. Viscous effects. Aircraft wake vortices. Ring vortices. Separated flows. Second term: Survey of finite difference, finite element, and spectral approximations for solution of the Navier-Stokes equations in two and three dimensions. Numerical study of problems of hydrodynamic stability, transition, and turbulence. Third term: Methods for the numerical solution of the compressible Euler and Navier-Stokes equations in one, two, and three dimensions. Finite-difference and finite-volume methods. Methods based on solution of the Riemann problem. Flux-splitting. Shock-capturing methods and related stability problems. Kinetic-theory-based methods. Explicit and implicit artificial viscosity for the Euler equations. Total variation diminishing approximations. Implementation of algorithms on parallel architectures. Instructor: Leonard.

Ae 233. Hydrodynamic Stability. *9 units (3-0-6); second term. Prerequisites: 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, Richtmeyer-Meshkov, and other instabilities. The Orr-Sommerfeld equation, the dual role of viscosity, and boundary-layer stability. Effects of pressure gradient, suction and heat transfer in liquids and gases. Global and convective instabilities. Active control in the transition regime. Weakly nonlinear stability theory. Instructor: Dimotakis.

Ae 234. Hypersonic Aerodynamics. *9 units (3-0-6); third 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 2000–2001.

Ae 235. Rarefied Gasdynamics. *9 units; third term.* Molecular description of matter; distribution functions; discrete-velocity gases. Kinetic theory: free-path theory, internal degrees of freedom. Boltzman equation: BBGKY hierarchy and closure, H theorem, Euler equations, Chapman-Enskog procedure. Collisionless and transitional flows. Direct simulation Monte Carlo methods. Applications. Instructor: Pullin.

Ae 236. Separated Flows. *9 units (3-0-6); third term.* Topics include a review of boundary layer theory, Kirchhoff model of separation, triple-deck theory, Sychev model, effect of turbulence on separation, location of separation points in various practical applications, classes of three-dimensionality, separation in three-dimensional steady flow, topological structure of steady three-dimensional separation, open separation, local solutions, and shock-wave boundary-layer interaction. Not offered 2000–2001.

Ae 237 ab. Nonsteady Gasdynamics. *9 units (3-0-6); third term.* (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. (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. Instructor: Shepherd.

Ae 238. Sources of Vorticity. *9 units (3-0-6); first term.* Torque exerted on element of fluid by stress distribution. Conditions at a solid boundary. The baroclinic torque, compressibility, stratification. Effects of viscoelasticity and turbulence. Accelerated reference frames, and body forces. Unorthodox boundary conditions. Vorticity production due to discretization errors in numerical computations. Instructor: Hornung.

Ae 239 ab. Turbulence. *9 units (3-0-6); second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM 101; Ae 201 abc (may be taken concurrently).* Homogeneous isotropic turbulence and structure of fine scales. Reynolds-averaged equations and the problem of closure. Physical and spectral models. Subgridscale modeling. Structure of scalar fields, fractals, and irregular level sets. Turbulent mixing. Not offered 2000–2001.

Ae 240. Special Topics in Fluid Mechanics. *Units to be arranged.* Subject matter changes depending upon staff and student interest. Instructor: Staff.

Ae 241. Special Topics in Experimental Fluid and Solid Mechanics. *9 units (3-0-6). Prerequisites: Ae/APh 104 or equivalent or instructor's permission.* Selected topics, to be announced, subject matter depending on current interests. Instructor: Dimotakis.

Ae 242. Natural Aero and Hydrodynamics. *9 units (3-0-6); second term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Boundary layers: atmospheric boundary layers and Eckman boundary layer. Vortices in nature: twisters, tornadoes, and hurricanes. Separation phenomena: wind forces. Stratified and rotating flows: geostrophic and 2-D flows. Wakes and jets in nature. Buoyant convection. Clouds and down bursts, phase transitions in natural flows. Waves in nature: explosive waves, tidal waves, mountain waves, noise in nature. Not offered 2000–2001.

Ae 243. Biofluid Mechanics. *9 units (3-0-6); third term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Physical principles of fluid flow, definitions, dimensional analysis, conservation laws, vortex dynamics. Life in moving fluids: shapes and drag, lift, airfoils, gliding and soaring, making and using vortices, the thrust of flying and swimming, life in shear flows. Internal flows: flows within pipes and cavities, internal flows in organisms. Human circulatory system: the heart, veins, and arteries (microcirculation). Fluid mechanics of respiratory system. Life in very low Reynolds number flows. Not offered 2000–2001.

ANTHROPOLOGY

An 22. Introduction to the Anthropology of Development. *9 units (3-0-6); second term.* Introduction to the study of social change in contemporary tribal and peasant societies. Emphasis on the impact of modernization, especially through urbanization, industrialization, and the intensification of agriculture. Instructor: Ensminger.

An 101. Selected Topics in Anthropology. *9 units (3-0-6). Offered by announcement.* Instructors: Staff, visiting lecturers.

An 123. The Anthropology of Rapid Social Change. *9 units (3-0-6); third term. Prerequisite: An 22.* Detailed studies of selected peasant and tribal societies in developing areas, focusing on two types of rapid social change: that which is induced from outside through the efforts of government and other planning organizations, and that which is induced from within through local experimentation, innovation, revitalization, and migration. Instructor: Staff. Not offered 2000–2001.

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, or equivalents.* Introduction to functions of a complex variable; linear ordinary differential equations; special functions; eigenfunction expansions; integral transforms; linear partial differential equations and boundary value problems. Instructors: Bruno, Meiron.

ACM 101. Ordinary Differential Equations. *9 units (3-0-6); first term. Prerequisite: ACM 100 abc instructor's permission.* Basics of linear and nonlinear ODEs, phase plane, Poincaré-Bendixon theorem, stability, Floquet theory, regular and irregular singular points, expansions about irregular singular points, asymptotic expansions for ODEs, perturbation theory, boundary layer theory, WKB theory, multiple scales. Instructor: Cohen.

ACM 102 ab. Partial Differential Equations. *9 units (3-0-6); second, third terms. Prerequisite: ACM 101 or instructor's permission.* First-order partial differential equations (PDEs); classification of PDEs; Cauchy-Kowalewski theorem; separation of variables; spectral theory operators; Laplace, Poisson, and wave equations; Huyghens principle; Green's functions; well-posed vs. ill-posed problems; introduction to nonlinear PDEs; Burger's equation; shock waves; KdV equation. Instructor: Cohen.

ACM 103. Complex Variables. *9 units (3-0-6); first term. Prerequisite: ACM 100 abc or instructor's permission.* Advanced overview of complex variables. Topics: Contour integration, analytic continuation, series expansions, multivalued functions, normal families, Plemelj formulas, conformal mapping, asymptotic expansions, saddle-point method. Instructor: Amundsen.

ACM 104. Matrix Theory. *9 units (3-0-6); second term. Prerequisite: ACM 100 abc or instructor's permission.* Matrices and determinants, linear algebra, theory of linear equations, least-square methods, eigenvalues, eigenvectors, Gram-Schmidt orthogonalization process, positive definiteness, simultaneous diagonalization, canonical forms, matrix analysis of differential equations, stability of ordinary differential equations. Variational principles and perturbation theory. Instructor: Amundsen

ACM 110. Introduction to Numerical Analysis: Approximation Theory and Ordinary Differential Equations. *9 units (3-0-6); first term. Prerequisite: ACM 100 abc or instructor's permission.* Approximation theory: interpolation by polynomials, rational functions, trigonometric functions, numerical quadrature, Gaussian integration; numerical integration of ODEs: initial value problems, one-step methods, multistep methods, error analysis and stability analysis, stiff systems, boundary value problems, shooting and multiple shooting methods. Instructor: Hou.

ACM 111. Introduction to Numerical Analysis: Numerical Linear Algebra. *9 units (3-0-6); second term. Prerequisite: ACM 100 abc or instructor's permission.* Gaussian elimination, LU factorization, Cholesky decomposition, error analysis, Householder and Gram-Schmidt orthogonalization, Schur normal form, computation of eigenvalues and eigenvectors, QR method, singular value decomposition, Lanczos and Arnoldi methods, pseudospectra, nonlinear systems and Newton's method, iterative methods for large linear systems, relaxation methods, conjugate gradient methods, multigrid method. Instructor: Zhou

ACM 112. Introduction to Numerical Analysis: Partial Differential Equations. *9 units (3-0-6); third term. Prerequisite: ACM 100 abc or instructor's permission.* Finite difference methods for linear hyperbolic and parabolic PDEs, stability analysis; finite element methods for parabolic and elliptic PDEs, variational, Galerkin and collocation formulations; ADI method; introduction to shock capturing methods for nonlinear hyperbolic equations, level set methods for moving interfaces, projection methods for incompressible Navier-Stokes equations. Instructor: Zhou

ACM 113. Introduction to Optimization. *9 units (3-0-6); third term. Prerequisite: ACM 100 abc or instructor's permission.* Unconstrained optimization: first and second order conditions, Newton-like methods, conjugate direction methods, trust region methods. Constrained optimization: linear programming, general theory for nonlinear constrained optimization, quadratic programming and general linearly constrained optimization, nonlinear programming, optimizing functionals using the calculus of variations. Combinatorial optimization: integer programming, dynamic programming. Instructor: Pierce.

ACM 190. Reading and Independent Study. *Units by arrangement.* Graded pass/fail only.

ACM 201 ab. Advanced Partial Differential Equations. *9 units (3-0-6); first, second terms. Prerequisite: ACM 100 abc or instructor's permission.* This two-term course is an introductory course in the modern theory of PDEs. The first term will cover linear equations, including transport equations, Laplace's equation, the heat equation as well as the wave and Schroedinger's equations. In the second term the interest will shift to nonlinear problems with particular attention paid to nonlinear elliptic and parabolic equations and to conservation laws and Hamilton-Jacobi equations. Instructor: Guidotti.

ACM 210 abc. Advanced Numerical Methods for PDEs. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 110,111,112, or instructor's permission.*

a. Finite difference and finite volume methods for hyperbolic problems: Analysis and design of non-oscillatory schemes for linear scalar convection, nonlinear scalar conservation laws and systems of nonlinear conservation laws; extensions to multiple dimensions; adjoint error correction for functionals.

b. Finite element methods for elliptic problems: A priori and a posteriori error analysis of the finite element method for the Poisson problem; construction of finite element matrices and solution via multigrid. Elliptic problems with multiscale coefficients.

c. 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. Instructors: Pierce, Hou.

ACM 214. Methods of Tomography and Computational Electromagnetism. *9 units (3-0-6); first, second terms. Prerequisite: ACM 95/100 or equivalent.* Discrete Fourier transform (DFT) and its properties. Applications of DFT to integration, interpolation, and digital filtering. Radon transform, properties, inversion formulas, relation to the Fourier transform. Tomography algorithms. Fundamentals of electromagnetism. Problems of electrostatics and Laplace equations. The variational principle. Integral equation techniques for the interior and exterior boundary problems. Acoustic waves and Helmholtz equations. Addition theorem, boundary integral equations, Maxwell's equations. Exact and approximate methods in wave propagation: Born-Rytov approximations, geometrical optics, fast methods. Inverse problems. The course will contain a variety of computational exercises and projects. Instructor: Kunyansky.

Ae/ACM 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aeronautics.

ACM 290 abc. Applied and Computational Mathematics Colloquium. *1 unit (1-0-0); 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

AM 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. Instructor: Mason.

AM 65. Mechanics of Materials. *9 units (3-0-6); first term. Prerequisites: AM 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. Instructor: Heaton.

AM 66. Vibration. *9 units (3-0-6); third term. Prerequisites: AM 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.

Ae/AM/CE 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aeronautics.

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, differential equations, stability, perturbation theory. Applications to problems in engineering and science are stressed. Instructor: Beck.

AM 151 abc. Dynamics and Vibrations. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc or instructor's permission.* Variational principles and Lagrange's equations. Response of mechanical systems to periodic, transient, and random excitation. Free and forced response of discrete and continuous systems. Approximate analysis methods. Introduction to nonlinear oscillation theory and stability. Instructor: Iwan.

Ae/AM 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aeronautics.

AM 165ab. Elasticity. *9 units (3-0-6); second, third terms. Prerequisites: Ae/AM 160 a and registered in Ae/AM 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. Instructor: Bhattacharya.

AM 175 abc. Advanced Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: AM 125 abc and AM 151 abc or equivalents.* Topics include linear and nonlinear vibrations of discrete and continuous systems, stability and control of dynamical systems, and stochastic processes with applications to random vibrations. Not offered every year.

AM 176 abc. Nonlinear Dynamical Systems and Chaos. *9 units (3-0-6); first, second, third terms. Prerequisites: AM 125 abc, or instructor's permission.* Basic ideas from dynamical systems theory. One-dimensional maps, circle maps, rotation numbers, kneading theory, strange attractors, structural stability, hyperbolicity, symbolic dynamics, invariant manifolds, Poincaré maps, the Smale horseshoe. Techniques of local bifurcation theory are developed with emphasis on center manifolds and normal forms, global bifurcations, chaos, homoclinic and heteroclinic motions. Applications will be taken from a variety of areas, including fluid mechanics, structural mechanics, control theory, circuit theory, orbital mechanics, condensed-matter physics, and classical field theory. Not offered every year, but see CDS 140 and CDS 240.

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 209 abc. Seminar in Solid Mechanics. *1 unit (1-0-0).* For course description, see Aeronautics.

Ae/AM/MS 213 abc. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aeronautics.

Ae/AM/CE 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aeronautics.

Ae/AM 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aeronautics.

AM/Ae 220 ab. Elastic Stability of Structures and Solids. *9 units (3-0-6); second, third terms. Prerequisite: Instructor's permission.* Introduction to the notions of stability and bifurcation of elastic systems using simple examples. Koiter's general asymptotic theory for the buckling, post-buckling, mode interaction, and imperfection sensitivity in elastic systems. One-dimensional problems include the elastica, thin-walled beams, circular arches, trusses, and frames. Two-dimensional examples include flat plates with simple or multiple buckling loads and circular cylinders under lateral pressure or axial compression. Extension to continuum solid mechanics includes plane strain and simple three-dimensional problems. Not offered every year.

Ae/AM 223. Plasticity. *9 units (3-0-6).* For course description, see Aeronautics.

Ae/AM 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aeronautics.

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.

APh 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 9 a is a prerequisite for enrollment in APh 9 b.* Introduction to solid-state electronics, including physical modeling and device fabrication. Topics: semiconductor crystal growth and device fabrication technology, carrier modeling, doping, generation and recombination, pn junction diodes, MOS capacitor and MOS transistor operation, and deviations from ideal behavior. Laboratory includes computer-aided layout, and fabrication and testing of light-emitting diodes, transistors, and inverters. Students learn photolithography, and use of vacuum systems, furnaces, and device-testing equipment. Instructor: Scherer.

APh 17 abc. Thermodynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Introduction to the use of thermodynamics and statistical mechanics in physics and engineering. Entropy, temperature, and the principal laws of thermodynamics. Canonical equations of state. Applications to cycles, engines, phase and chemical equilibria. Probability and stochastic processes. Kinetic theory of perfect gases. Statistical mechanics. Applications to gases, gas degeneration, equilibrium radiation, and simple solids. Instructors: Quake, Crocker.

APh 23. Demonstration Lectures in Optics. *6 units (2-0-4); first term. Prerequisite: Ph 1 abc.* Nine lectures 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. Instructors: Crocker, Shumate.

APh 24. Introductory Modern Optics Laboratory. *6 units; second 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. Instructors: Crocker, Shumate.

APh 25. Introductory Quantum Mechanics. *9 units (3-0-6); third term. Prerequisites: Ph 2 ab, Ma 2 ab, or equivalents.* Introduction to quantum mechanics: Schrödinger equation, uncertainty principle, postulates of quantum mechanics, wave packets, dispersion, abrupt potentials, harmonic oscillator, angular momentum. Instructor: Quake.

APh 77 bc. Laboratory in Applied Physics. *9 units; 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. Instructors: Goodwin and staff.

APh 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research experience, open only to senior 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. Instructors: Culick and applied physics faculty.

APh 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research experience, open only to senior 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 pass/fail basis. This course cannot be used to satisfy the laboratory requirement in APh. Instructors: Culick and applied physics faculty.

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 Aeronautics.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6 first term; 1-3-5 second and third terms).* For course description, see Aeronautics.

APh 105 abc. States of Matter. *9 units (3-0-6); first, second, third terms. Prerequisite: APh/ME 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. Instructor: Johnson.

APh 107. Advanced Dynamics. *9 units (3-0-6); third term. Prerequisite: dynamics at level of Ph 106 ab.* Review of Hamilton and Hamilton-Jacobi formalisms; integrable systems; continuous and discrete dynamics (maps); the KAM analysis; solitons; dissipative systems and fractal sets; a variety of examples. Not offered every year.

APh 110. Topics in Applied Physics. *2 units (2-0-0); first, second terms.* A seminar course designed to acquaint juniors and first-year graduate students with the various research areas represented in the option. Lecture each week given by a different faculty member of the option, reviewing, in general terms, his or her field of research. Graded pass/fail. Instructors: Bellan and applied physics faculty.

APh 114 abc. Solid-State Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: APh 25 and APh 125 ab or 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. Instructor: Atwater.

APh 124. Advanced Modern Optics Laboratory. *9 units; third term. Prerequisites: APh 24, APh 130, APh 131 (or APh 190 ab).* Laboratory experiments covering both active and passive optical devices and topics relevant to their use in modern optical systems. Topics covered include propagation effects in optical fibers; fiber-optic traveling-wave amplifiers; gain saturation and saturation dynamics in optical amplifiers; sources for fiber-optic systems including semiconductor lasers and fiber lasers; direct modulation, external modulation of laser sources; noise in laser sources. Instructor: Shumate.

APh 125 abc. Quantum Mechanics of Matter. *9 units (3-0-6); first, second, third terms. Prerequisite: APh 25.* Quantum mechanics and applications to problems in solids, liquids, and gases. Topics: central force problems; hydrogen atom; multielectron atoms; approximation methods: time-independent and time-dependent perturbation theory, variational method, WKB approximation; eigenstates of molecules; theories for chemical bonding; optical transitions in matter; scattering: Born approximation, partial wave expansions, electron and photon scattering in matter; the electromagnetic field; quantum theory of crystalline solids. Not offered 2000–2001.

APh/EE 130 abc. Introduction to Optoelectronics and Optoelectronic Devices. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 23, 24, or instructor's permission.* Introduction to phenomena, devices, and applications of optoelectronics. Gaussian beam propagation, optical resonators. Interaction of light and matter, 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. System design considerations, with examples from optical communications, radar, and other applications. Instructor: Shumate.

APh/EE 132. Fourier Optics. *9 units (3-0-6); third term. Prerequisite: ACM 95/100 abc.* Fourier transform techniques are used to describe light propagation through homogeneous media and thin optical elements (lenses, gratings, holograms); applications to modern optical systems are discussed. Topics: scalar diffraction theory; the lens as a Fourier transforming element; coherent and incoherent imaging; optical information processing systems; holography. Not offered 2000–2001.

APh 133. Optical Computing. *9 units (3-0-6); second term. Prerequisite: APh/EE 132 or equivalent exposure to optics.* An introductory course in devices and techniques used for the optical implementation of information processing systems. Subjects to be covered include optical linear transformations, nonlinear optical switching devices, holographic interconnections, optical memories, photorefractive crystals, and optical realizations of neural computers. Instructor: Psaltis.

APh/MS 140. Ion Beam Modification and Analysis of Materials. *6 units (2-0-4); first term.* Introduction to ion-solid interactions as applied to the modification of thin films and to the structural and compositional analysis of materials. Topics: collision kinematics, interatomic potentials, scattering cross sections, stopping cross sections, energy straggling, transport theory, ion ranges. Applications to backscattering spectrometry: energy and mass resolution, scattering geometry, evaluation of spectra, channeling. Applications to materials modification: ion implantation, mixing, sputtering, amorphization. Not offered 2000–2001.

APh/MS 141 bc. Microscopic Imaging, Diffraction, and Spectroscopy Laboratory. *9 units; second, third terms.* Laboratory experiments that investigate basic principles of microscopic imaging, diffraction, and spectroscopy, and their application to analysis of materials. The experiments are designed to illustrate the power of analytic techniques through an understanding of basic instrumental operation as well as common issues such as resolution, magnification, aberrations, signal-to-noise, dynamic range, and systematic instrumental artifacts. Experiments investigate techniques such as optical microscopy, scanning tunneling microscopy, Auger electron spectroscopy/microscopy, Fourier-transform infrared spectroscopy, X-ray photoelectron spectroscopy, X-ray diffraction, and Rutherford backscattering spectrometry. Students perform three experiments per term and may register for multiple terms. Experiments may vary from year to year. Not offered 2000–2001.

APh 150. Topics in Applied Physics. *Units and term 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. Instructors: Quake, Corngold, staff.

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 multi-tiered 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.

EE/APh 180. Solid-State Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

APh/EE 183 abc. Fundamentals of Electronic Devices. *9 units (3-0-6); first, second, third terms.* Introduction to the fundamentals of modern electronic and optoelectronic devices. Topics include pn junctions, bipolar transistors, field-effect transistors, magnetic devices, light-emitting diodes, lasers, detectors, solar cells, chemical sensors, and MEMS. Emphasis will be placed on nanostructures and nanofabrication techniques. Where appropriate, integration and systems-level issues will be included. Instructor: McGill.

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 2000–2001.

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.

APh 214 abc. Advanced Solid-State Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 114 abc and Ch 125 abc or Ph 125 abc.* Course in experimental and theoretical solid-state physics. Topics: phonons; electronic excitation in solids; electron-phonon interactions; optical transport and magnetic properties; superconductivity; ferroelectricity. Emphasis will be mainly theoretical, with frequent comparison between theoretical predictions and experimental results. Not offered 2000–2001.

Ph/APh 223 abc. Advanced Topics in 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. Instructors: 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

These courses are open only to students who have fulfilled the freshman humanities requirement.

Art 101. Selected Topics in Art History. *9 units (3-0-6). Offered by announcement.* Instructors: Staff.

Art 103. Ancient Art: From the Pyramids to the Colosseum. *9 units (3-0-6).* A survey of the art of the earliest civilizations of the Ancient Near East and Mediterranean from the Bronze Age to approximately 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 Graeco-Roman art, the foundation of the Western artistic tradition. The course will include one or more study trips to the Getty Museum. Instructor: Woods.

Art 106. The Age of the Great Cathedrals. *9 units (3-0-6).* 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, from 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. Instructor: Howard.

Art 108. 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. Instructor: Howard. Not offered 2000-2001.

Art 109. 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, Velasquez, Rubens, Hals, and Rembrandt. Instructor: Howard. Not offered 2000-2001.

Art 110. Baroque Art. *9 units (3-0-6); third 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. Instructor: Howard. Not offered 2000-2001.

Art 111. European Art of the 18th Century: From the Rococo to the Rise of Romanticism. *9 units (3-0-6); first term.* 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. Instructor: Bennett. Not offered 2000-2001.

Art 112. British Art. *9 units (3-0-6).* A survey course on British painting, sculpture, and architecture in the 17th, the 18th, and the 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 which 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 115. 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. Instructor: Bennett. Not offered 2000-2001.

Art 118. 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. Instructor: Staff.

Art 125. History of Western Architecture. *9 units (3-0-6).* A survey of major developments in Western architecture and urbanism from the classical civilizations of Greece and Rome to the 20th century. The course focuses upon the visual, spatial, and functional properties and the cultural significance of key building types ranging from Greek temples, Roman civil and administrative structures, Gothic cathedrals, Renaissance and baroque churches and city palaces, to the technology-based skyscrapers and other forms of 20th-century modernism. Instructor: Howard.

Art 150. 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 2000-2001.

Art 151. Traditions of Japanese Art. *9 units (3-0-6).* 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.

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. Instructor: Scoville. Additional information concerning this course can be found at http://astro.caltech.edu/academics/ay1/.

Ge/Ay 11 c. Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 20. Basic Astronomy and the Galaxy. *9 units (3-0-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc, or for freshmen with a strong high-school background in math and physics.* Astronomical terminology. Stellar masses, distances, and motions. Star clusters and their galactic distributions. Stellar spectra, magnitudes, and colors. Structure and dynamics of the galaxy. Instructor: A. Sargent.

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); second term. Prerequisite: Ay 20.* The extragalactic distance scale. Clusters of galaxies. Introduction to cosmology. Balance of matter and radiation in the universe. Cosmological tests and parameters. Fundamental properties of galaxies. Galaxy formation and evolution. Large-scale structures. Active galactic nuclei. Diffuse extragalactic backgrounds. Instructor: Blandford.

Ay 30. Current Trends in Astronomy. *3 units (2-0-1); second term.* Weekly seminar primarily for sophomore astronomy majors. 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. Fulfills Institute communications requirement for Ay majors. Graded pass/fail. Instructor: W. Sargent.

Ay 43. Reading in Astronomy and Astrophysics. *Units in accordance with work accomplished.* Student must have a definite reading plan and obtain permission of instructor before registering. Graded pass/fail.

Ay 78 abc. Senior Thesis. *9 units; second term. 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. This research must be supervised by a faculty member, your thesis adviser. 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.* Physics of stellar atmospheres. Properties of stars, stellar spectra, radiative transfer, line formation. Stellar structure, stellar evolution, evolution of binaries. Nucleosynthesis in stars. Stellar oscillations. Instructors: W. Sargent, Cohen.

Ay 102. Physics of the Interstellar Medium. *9 units (3-0-6); second term. Prerequisite: Ay 20.* An introduction to fluid mechanics, sound waves, and shock waves. Introduction to magnetohydrodynamics, Alfvén waves, and plasma waves, with applications to the interstellar medium. Supernova remnants. The interstellar magnetic field. The physics of H I and H II regions. Instructors: W. Sargent, Scoville.

Ge/Ay 103. Introduction to the Solar System. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 105. Optical Astronomy Instrumentation Lab. *9 units (1-6-2); second term. Prerequisite: Ay 20.* An opportunity for astronomy and physics undergraduates (juniors and seniors) to gain firsthand experience with the basic instrumentation tools of modern optical and infrared astronomy. The 10 weekly lab experiments are expected to include radiometry measurements, geometrical optics, optical aberrations and ray tracing, spectroscopy, fiber optics, CCD electronics, CCD characterization, photon counting detectors, vacuum and cryogenic technology, and stepper motors and encoders. Instructor: Steidel.

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisites: Ay 101 (undergraduates); Ph 125 or equivalent.* The interaction of radiation with matter: radiative transfer, emission, and absorption. Compton processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructors: Phinney, Goldreich.

Ay 122. Astronomical Measurements and Instrumentation. *9 units (3-0-6); second term. Prerequisite: Ph 106 or equivalent.* Measurement and signal analysis techniques throughout the electromagnetic spectrum. Telescopes and interferometers; detectors and receivers; photometry and radiometry; imaging devices and image processing; spectrometers; space telescopes. Instructors: Steidel, A. Sargent.

Ay 123. Structure and Evolution of Interacting Binary Stars. *9 units (3-0-6); third term. Prerequisites: Ay 101 (undergraduates); Ph 125 or equivalent.* Stellar structure and evolution in the context of exotic interacting binary stars (cataclysmic variables, X-ray binaries, black hole binaries, binary pulsars). Energy transport, nuclear fusion, stellar atmospheres (including external heating), loss of mass and angular momentum, advanced stages of evolution, tidal forcing, rotation, and magnetic dynamos will be covered with application to recent research on interacting binary stars containing compact objects. Instructor: Phinney.

Ay 124. Structure and Dynamics of Galaxies. *9 units (3-0-6); first term. Prerequisites: Ay 21 (undergraduates); Ph 106 or equivalent.* Stellar dynamics and properties of galaxies; kinematics and dynamics of our galaxy; spiral structure; stellar composition, masses, and rotation of external galaxies; star clusters; galactic evolution; binaries, groups, and clusters of galaxies. Instructor: Ellis.

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); second term. Prerequisites: Ay 21 (undergraduates); Ph 106 or equivalent.* 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: Readhead.

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: W. Sargent, Scoville.

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); third term. Prerequisites: Ay 21 (undergraduates) and Ph 106 or equivalent.* Cosmology; extragalactic distance determinations; relativistic cosmological models; galaxy formation and clustering; thermal history of the universe, microwave background; nucleosynthesis; cosmological tests. Instructor: Djorgovski.

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, Evolution, and Detection of Planetary Systems. *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 by astronomy students on current research. These provide an opportunity for practice in the organization and presentation of reports. A minimum of two presentations will be expected from each student each year. The presentations will be video-

taped and critiqued by peers. This course fulfills the Institute communications 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: Ellis.

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. Not offered 2000–2001.

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. Not offered 2000–2001.

Ay/EE 144. Imaging at Radio, Infrared, and Optical Wavelengths by Interferometric and Adaptive Techniques. *9 units (3-0-6); third term.* The theory of coherence, interferometry, and aperture synthesis observations at radio and visible wavelengths. The technique of adaptive optics to overcome atmosphere blurring at visible wavelengths. Emphasis is given to the formation of images with limited spatial frequency coverage, to applications in astronomy, geodesy, and high-resolution imaging with large optical telescopes. Relative emphasis on interferometric imaging versus adaptive optics will vary from year to year. Not offered 2000–2001.

Ay/Ph 145. Signal Processing and Data Analysis. *9 units (3-0-6); third term.* Statistical analysis and signal processing essential to observational and to experimental science. Topics: calculus of probability, Bayes theorem, distributions of single and multiple random variables, normal samples, parameter estimation, time series analysis of signals, Fourier transforms, convolution and correlation, sampling and digitizing, power spectrum measurement, digital filters. Examples from astronomy and physics. Not offered 2000–2001.

Ay 211. Extragalactic Astronomy. *9 units (3-0-6); first term. Prerequisites: Ay 127, Ay 124, and Ay 123.* Not offered 2000–2001.

Ay/Ph 212. Topics in Astronomy: Cosmology and Particle Structure. *9 units (3-0-6); third term.* This course will cover our current understanding of structure formation and cosmology and will form links with observations and numerical simulations. Topics: overview of basic FRW cosmology; growth of linear perturbations; CMBR anisotropies; nonlinear evolution of dark matter density contrast; abundances of structures; numerical simulation of dark matter; formation of baryonic structure; Universe at z<10 (absorption systems, high-z galaxies, IGM); hydro simulations; inflation and the very early Universe. Not offered 2000–2001.

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 changes each time the course is offered. Not offered 2000–2001.

Ay 218. High-Energy Astrophysics. *9 units (3-0-6); second term. Prerequisites: Ay 125, Ph 106, and Ph 125 or equivalent.* This course will primarily focus on gamma-ray bursts (GRBs) and soft gamma-ray repeaters (SGRs). These two objects are excellent physical laboratories of relativistic shocks and super-strong magnetic fields, respectively. Topics: observational summary of GRBs and afterglow emission; propagation, particle acceleration, and radiation from relativistic shocks; observational summary of SGRs and associated plerions; and super-strong magnetic fields inside neutron stars and their effects on photons outside. Graded pass/fail. Not offered 2000–2001.

Ph/Ay 221 abc. Cosmology and Particle Astrophysics. *9 units (3-0-6).* For course description, see Physics.

Ge/Ay 226. Observational Planetary Astronomy. *9 units (3-3-3).* For course description, see Geological and Planetary Sciences.

Ay 235. Research Seminar. *1 unit (1-0-0); third term.* Will present seminars on current research interests of the astronomy faculty to graduate students during the fall term. Instructors: Staff. Not offered 2000–2001.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

BMB/Bi/Ch 170. Principles of Three-Dimensional Protein Structure. *9 units (3-3-3); first term. Prerequisites: Bi/Ch 110.* The forces determining the folding of proteins into their unique tertiary structures. Protein structures will be classified by organization of the structural elements and structural motifs, and their influence on function will be explored. Topics will include enzyme and antibody structure and function, virus structures, protein-nucleic acid interactions, methods of macromolecular structure determination, and protein structure analysis. A computer graphics system will be used for the display and analysis of macromolecular structure. Instructors: Bjorkman and Rees.

BMB 176. The Molecular Basis of Protein Function. *9 units (3-0-6); second term. Prerequisite: BMB/Bi/Ch 170.* Theory, mechanisms, and kinetics of protein-ligand interactions and enzyme catalysis, including the role of cofactors. The course will also cover the cooperativity characteristic of multisubunit protein complexes and will emphasize the relationship between protein structure and function. Instructors: Mayo and Roberts.

BMB 178. Fundamentals of Molecular Genetics. *9 units (3-0-6); third term. Prerequisite: BMB 176.* Principles and mechanisms of DNA repair and replication, transcription and splicing, and protein synthesis. Instructors: Abelson, Campbell, Parker.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit (1-0-0).* For course description, see Biology.

BMB 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BIOLOGY

Bi 1. Drugs and the Brain. *9 units (4-0-5); third term.* This course introduces nonbiologists to recent advances in biology, biomedical science, and applied biology. The scientific community is beginning to understand the mechanisms of drug addiction, the causes of major neurological diseases, and some medical therapies for these diseases. Because many of these advances involve molecular biology and genetics, the course treats the fundamental aspects of drug actions on the nervous system, from the quantitative, molecular, physical, and chemical viewpoints. Instructors: Lester, TBA.

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. Instructors: Abelson, Revel, and staff.

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. Graded pass/fail. Instructor: Varshavsky.

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: Dunphy and 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 12. Introduction to Developmental Biology. *9 units (3-0-6); second term. Prerequisite: Bi 1 or 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 mechanisms underlying morphogenetic movements, differentiation, and interactions during development, covering both classical and modern approaches to studying these processes. Instructor: Bronner-Fraser.

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. Instructors: Staff.

Bi 23. Biology Tutorial. *Units to be arranged; maximum of 6 units per term; second, third terms.* Study and discussion of special problems in biology, usually involving regular tutorial sessions with instructors. To be arranged through the instructor before registration. Graded pass/fail. Instructors: Strauss and staff.

Bi 80. Biology Major Seminar. *3 units (1-0-2); first term. Prerequisite: Bi 9 or permission of instructor.* May be repeated for credit, with permission of instructor. Discussions and student presentations designed for biology majors from sophomores to seniors, to provide information and practice oral communication techniques. Topics will include career choices, admission to medical or graduate school, student research projects including senior thesis research, and current biological topics of interest. Graded pass/fail. Instructors: Revel, Schuman.

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, concurrent registration for Bi 80 during first term, 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. Instructors: Revel and staff.

Ph/Bi 103 c. Neuroscience for Physicists and Engineers. *Third term.* For course description, see Physics.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8); first term. Prerequisite: Ch 41 abc or consent of instructor.* 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. Prerequisite: 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 and staff.

Bi 114. Immunology. *12 units (4-0-8); 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. Instructors: Alberola-Ila, Bjorkman, Rothenberg.

Bi 115. Virology. *6 units (2-0-4); third term. Prerequisites: Bi 8, Bi 9.* Introduction to the chemistry and biology of viruses. Emphasis on replication strategies of animal viruses, with consideration also given to epidemiology of viruses, nature and control of virus diseases, evolution of viruses, and some aspects of bacterial and plant virus replication. Given in alternate years; not offered 2000–2001. Instructor: Strauss.

CNS/Bi 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. Instructors: Hay, Meyerowitz, Sternberg.

Bi 123. Genetics Laboratory. *9 units (0-6-3); 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 and staff.

Bi 125. Principles and Methods of Gene Transfer and Gene Manipulation in Eukaryotic Cells. *6 units (2-0-4); second term. Prerequisite: Bi/Ch 110.* Lecture and discussion course dealing with modern approaches to "genetic intervention" in eukaryotic cells. Topics: mutagenesis of cultured animal cells and selection schemes; gene transfer into cultured cells mediated by naked DNA, chromosomes and viruses; transformation of yeast by chromosomal DNA and plasmids; neoplastic transformation of plant cells by *Agrobacteria* plasmids; nuclear transplantation and gene injection into amphibian eggs and oocytes; selective drug-induced gene amplification in cultured animal cells; somatic cell hybridization. Instructor: Attardi. Given in alternate years; not offered 2000–2001.

Bi 127. Regulation of the Cell Cycle. *6 units (2-0-4); third term. Prerequisites: Bi 8, Bi 9, Bi/Ch 110, or graduate standing. Enrollment by permission of instructor.* An advanced seminar focusing on regulation of the cell cycle in eukaryotes. Genetic, biochemical, and molecular studies of cell cycle control in different biological systems including yeast, vertebrate and invertebrate embryos, and vertebrate cells in culture will be featured. The relationship of cell proliferation, and the signals that control it, to cellular differentiation will be a theme. Critical review of current literature will be central. Instructor: Wold. Given in alternate years; offered 2000–2001.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6); second term. Recommended: 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. Not offered 2000–2001.

Bi/CNS 150. Neurobiology. *10 units (4-0-6); first term.* Lectures and discussions on general principles of the organization and function of nervous systems, providing both an overview of the subject and a foundation for advanced courses. Topics include neurocytology and gross neuroanatomy; developmental neurobiology; the biophysical basis for action potentials, synaptic transmission, and sensory transduction; and the integration of these processes in sensory and motor pathways of the central nervous system. Laboratory demonstrations offer experi-

ence with the experimental preparations discussed in the course. Instructors: Laurent, Zinn, Schuman.

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 permission of instructor.* A lecture and discussion course on the neurobiology of behavior. Topics may include biological clocks, eating behavior, sexual behavior, addiction, mental illness, and neurdegenerative diseases. Given in alternate years; not offered 2000–2001. Instructors: Patterson and Zinn.

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; offered 2000–2001.

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; not offered 2000–2001.

Bi/CNS 161. Cellular and Molecular Neurobiology Laboratory. *9 units (0-9-0); second term. Prerequisite: Bi 150 or instructor's permission.* Experiments on the molecules of membrane excitability—ion channels, receptors, and transporters. Students synthesize mRNA in vitro for these molecules from cDNA clones and inject the mRNA into *Xenopus* oocytes. Students then perform electrophysiological experiments on the oocytes, including voltage-clamp recording of macroscopic currents and patch-clamp recording of single channels. Students analyze the data to reveal quantitative biophysical concepts. Graded pass/fail. Instructor: TBA. Given in alternate years; not offered 2000–2001.

Bi/CNS 162. Central Nervous System Laboratory. *12 units (2-7-3); third term. Prerequisite: Bi 150 or instructor's permission.* A laboratory-based introduction to experimental methods used to study the central nervous system electrophysiologically. Through the term, students

investigate the physiological response properties of the mammalian cerebellum using various extracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, microelectrode fabrication, stimulus presentation, and computer-based data analysis. Graded pass/fail. Instructor: Bower. Given in alternate years; not offered 2000–2001.

Bi/CNS 163. Sleep and Dreams. *10 units (2-7-1); second term.* A research-oriented course addressing fundamental questions of sleep functions, mechanisms, and evolution. Topics include comparative analysis of sleep across species, sleep deprivation experiments, memory, hybernation, unihemispheric sleep, sleep disorders, functional neuroanatomy of non-REM and REM sleep, and neural mechanisms of arousal. Students will work in groups to design, carry out, and analyze experiments. Offered for grades only. Instructors: Koch, staff. Not offered 2000–2001.

Bi/CS 164. Projects in Bioinformatics. *9 units (3-3-3); third term. Prerequisites: Bi 8 and Bi 9 or approval of instructor.* Lecture, discussion, and projects in bioinformatics. Students will create, extend, and integrate bioinformatic software tools. Topics include genome-scale mRNA expression analysis, signal transduction pathway modeling, genome database analysis tools, and modeling morphogenesis from gene expression patterns. Each project will link into a larger Web application framework. Instructor: Mjolsness.

Env/Bi 166. Microbial Physiology. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Env/Bi 168. Microbial Diversity. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Bi/CNS 169. Methods in Computational Molecular and Cellular Biology. *12 units (3-7-2); second term. Prerequisite: Bi 8 or Bi 9 or equivalent; or instructor's permission.* A laboratory/presentation/discussion-based introduction to the use of computer modeling in molecular and cellular biology. The course will expose students to a range of computational questions raised by modern molecular and cellular experimental studies as well as currently available modeling tools to address these issues. Examples will be provided from research being performed in several Caltech laboratories. A major focus of course activity will be on student modeling projects, preferably related to their own laboratory research. Several modeling tools will be provided including the GENESIS simulation system developed at Caltech. Students should be familiar with molecular and cellular biology and a programming language. Instructor: Bower. Additional information concerning this course can be found at http://www.bbb.caltech.edu/bowerlab/Bi169/.

BMB/Bi/Ch 170. Principles of Three-Dimensional Protein Structure. *9 units (3-3-3).* For course description, see Biochemistry and Molecular Biophysics.

Bi/H 171. The History of Your Science. *9 units (3-2-4); third term. Prerequisites: active current involvement in research, or permission of instructors.* This is a presentation/discussion-based course focused on the influence of classical studies on modern science. Students in the course will be asked to identify, investigate, and give a presentation on a classical paper related to their own research interests. Presentations will consider 1) evidence that the paper selected is, in fact, a classic; 2) the historical context for the paper; 3) the way in which the paper has influenced the field since its original publication; and 4) the contemporary view of the paper as seen through current citations. Investigation of the paper will involve attempting to replicate the classical experimental results. Participation is not restricted by research area or subject matter. Instructors: Bower (biology); Winter (history).

CNS/Bi 172. Clinical Neuropsychology. *6 units (3-0-3).* For course description, see Computation and Neural Systems.

CNS/Bi 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

Bi 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. Coursework 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. Additional information concerning this course can be found at http://www.cco.caltech.edu/~lebert/bi180/index.html.

Bi 182. Developmental Gene Regulation and Evolution of Animals. *6 units (2-0-4); second term. Prerequisites: Bi 8, Bi 112, 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; diversificiation in the arthropods; and the special character of vertebrate evolution. Instructor: Davidson. Offered in alternate years; offered 2000–2001.

CNS/Bi/Ph 185. Collective Computation. *12 units (3-1-8).* For course description, see Computation and Neural Systems.

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); second 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. Instructors: Wold, Meyerowitz. Offered in alternate years; not offered 2000–2001.

Bi 189. Developmental Biology of Animals. *6 units (2-0-4); second term. Recommended prerequisite: Bi/Ch 110.* Lectures and discussions on various aspects of embryological development; cytoplasmic localization and cell interaction in early development, gene function and oogenesis, the role of accessory cells, gene regulation; the evolution of developmental processes, and patterns of macromolecular syntheses in early embryological life. Given in alternate years; not offered 2000–2001. Instructors: E. Davidson, Sternberg.

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*. Instructors: Sternberg, Meyerowitz. Offered in alternate years; not offered 2000–2001.

CS/CNS/Bi 191. Molecular Computation. *9 units (3-0-6).* For course description, see Computer Science.

Bi/Ch 202 abc. Biochemistry Seminar. *1 unit; first, second, third terms.* A seminar on selected topics and on recent advances in the field.

Bi 204. Genetics Seminar. *2 units; first term. Prerequisites: graduate standing, or Bi 122 and instructor's permission.* Reports and discussion on special topics in genetics. Instructor: Meyerowitz.

Bi 211. Topics in Membrane and Synaptic Physiology. *6 units (3-0-3); first term.* Graduate seminar discussing the original literature on the biophysics and molecular biology of ion channels, neurotransmitter receptors, transporters, and other molecules underlying the excitability of cell membranes. Instructor: Lester. Offered in alternate years; not offered 2000–2001.

Bi 212. Topics in Neuroethology. *6 units (2-0-4); second term.* Reading and discussions of original papers related to animal behavior and its analysis by neuroethological methods. Knowledge of neurophysiology is required. Instructor: Konishi. Offered in alternate years; not offered 2000–2001

Bi 214. Hematopoiesis: A Developmental System. *6 units (2-0-4); first term. Prerequisites: Bi 114 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. Offered in alternate years; not offered 2000–2001. Instructor: Rothenberg.

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. Given in alternate years; not offered 2000–2001. Instructor: Allman.

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; offered 2000–2001.

Bi 218. Molecular Neurobiology Graduate Seminar. *6 units (2-0-4); second term.* Topics to be announced. Instructor: Anderson.

Bi 219. Developmental Neurobiology. *12 units (3-0-9); second term.* Advanced discussion course involving extensive reading of current papers and student presentations. Topics: proliferation, migration, differentiation, and death of neurons; role of trophic factors, cell surface molecules, and hormones. Emphasis on the generation of specific synaptic connections and the molecular basis underlying it. Given in alternate years; not offered 2000–2001. Instructor: Fraser.

Bi 220. Advanced Seminar in the Molecular Biology of Development. *6 units (2-0-4); second, third terms.* Discussion of current papers on various pertinent topics including nucleic acid renaturation, hybridization, and complexity studies; synthesis and turnover of transcripts, transcript prevalence, and the dynamics of gene expression; transcription-level regulation of gene function; molecular aspects of differentiation in certain more intensely studied systems, etc. Quantitative aspects and biophysical background of relevant measurement methods are emphasized. Given in alternate years; not offered 2000–2001. Instructor: E. Davidson.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Bi 222. Structure and Function of the Synapse. *6 units (2-0-4); third term. Prerequisites: Bi 110 abc, Bi 150, graduate standing, or instructor's permission.* Lectures, reading, and discussion covering recent research on synaptic structure and function. Topics will include structure and function of synaptic proteins, emphasizing mechanisms of neurotransmitter release and regulation of post-synaptic receptors; the extracellular matrix and synaptic structure; protein kinase signalling cascades; and developmental and adult synaptic plasticity, emphasizing long-term potentiation and long-term depression. Reading and discussion will focus on evaluation of the primary research literature. Instructor: Kennedy. Given in alternate years; offered 2000–2001

Bi 224. Principles of bioLOGICal Analysis. *6 units (2-0-4); second term.* A graduate seminar course designed to illustrate how basic principles of logic and scientific methodology are applied to resolve questions about the function and regulation of biological systems. This course will draw upon examples from research papers in cellular and molecular biology to demonstrate how fundamental issues such as necessity and sufficiency, direct and indirect action, cause and effect, etc., underlie the execution and interpretation of most experiments in biology. The point of this course will be to give students a "conceptual tool kit" that they can apply to the resolution of experimental problems in any area of modern molecular and cellular biology. Instructor: Deshaies. Given in alternate years; offered 2000–2001.

Bi 225. Topics in Cellular and Molecular Genetics. *6 units (2-0-4); second term.* Reading and discussion of current papers on the theory and practice of "genetic intervention" in higher eukaryotic cells. Approaches will include DNA and chromosome-mediated transforma-

tion of cells in culture, gene amplification, cell fusion, gene injection into eggs, and use of somatic cell genetics techniques for gene cloning. Emphasis on the use of these approaches to study problems in areas such as cell differentiation, cell cycle control, cell compartmentation, and membrane physiology and assembly. Instructor: Attardi. Given in alternate years; not offered 2000–2001.

Bi 226. Topics in Genetics. *6 units (2-0-4); third term.* Reports and discussion on a broad range of topics in genetic analysis. Designed for graduate students intending a major or minor specialization in genetics. Instructors: Sternberg, Deshaies, Hay.

Bi 227. Methods in Modern Microscopy. *12 units (2-6-4); first term. Prerequisite: Approval of instructor.* 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 week-long 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*, zebrafish, chicken and *Xenopus* 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. Enrollment limited to 12 students, with preference 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.

Bi 241. Advanced Topics in Molecular Biology. *6 units (2-0-4); third term. Prerequisite: instructor's permission.* Reading and discussion of new areas in molecular biology.

Ge/Bi 244 ab. Paleobiology Seminar. *5 units.* For course description, see Geological and Planetary Sciences.

Ge/Bi 246. Geomicrobiology Seminar. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

CNS/Bi 246. Multicellular Recording. *9 units (2-6-1).* For course description, see Computation and Neural Systems.

CNS/Bi 247. Cerebral Cortex. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi 250 abc. Adventures in Biology. *9 units (3-0-6); first, second, third terms. Prerequisite: graduate standing.* Lectures and discussion covering the breadth of biology, research methods, logic, techniques and strategies, fundamental and general principles of modern biology, and unsolved problems. During this course, students will learn to read papers in a wide range of biological disciplines such as cell biology, developmental biology, immunology, molecular and systems neuroscience, structural biology, genetics, molecular biology, and biochemistry. Instructors: Biology staff.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit (1-0-0). Prerequisite: graduate standing.* Presentations and discussion of research at Caltech in biology and chemistry. Discussions of responsible conduct of research are included. Instructors: Sternberg, Deshaies, Hay.

Bi 260. How to Present a Seminar. *6 units (3-0-3); third term. Prerequisite: graduate standing in Biology, or instructors' permission.* General data presentation techniques, including how to design a seminar, how to develop or set up a problem, the design of clear visual aids, the appropriate and clear description of data, and the presentation of conclusions and future directions. We will also focus on general speaking skills and discuss how to give a good journal club presentation. Students will have the opportunity to practice speaking skills and work on individual presentations. Graded pass/fail. Given in alternate years; offered 2000–2001. Instructors: Laurent, Schuman.

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. Special Topics in CNS: Introduction to Mathematical Tools for Theoretical Neuroscience. *12 units (4-0-8).* For course description, see Computation and Neural Systems.

CNS/CS/Bi 288. Special Topics Seminar: DNA and Molecular Computation. *6 units (3-0-3).* 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 101. Introduction to Accounting. *9 units (3-0-6); first term.* An introduction to accounting in business. Topics include: financial accounting, cost accounting. Instructor: Freed.

BEM 102. Topics in Management Science. *9 units (3-0-6). Prerequisite: Ec 11. Offered by announcement.* Various management and industrial organization topics, including queuing, inventory and reliability theory, optimal stopping with applications to job search, and R&D. Underlying theory of simple stochastic processes will be developed as needed. Instructor: Camerer. Not offered 2000–2001.

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: Bossaerts.

BEM 104. Investment Analysis. *9 units (3-0-6); third term. Prerequisites: BEM 103, some familiarity with statistics. Ec 11 recommended.* An introduction to investment analysis, portfolio management, and capital markets. Its focus is the application of modern financial theory to portfolio selection and asset pricing. Topics include asset pricing models, the term structure of interest rates, contingent claim valuation. Instructor: Bossaerts.

BEM 105. Options. *9 units (3-0-6); third term. 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: Bossaerts.

BEM 110. Topics in Business Economics. *9 units (3-0-6). Prerequisite: consent of instructor. Offered by announcement.* Selected topics in business economics. Instructors: Staff.

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: Staff. Not offered 2000–2001.

Ec/BEM 163. Financial Intermediation. *9 units (3-0-6).* For course description, see Economics.

ChE 10. Introduction to Chemical Engineering Systems. *9 units (3-3-3); third term; open to freshmen only.* An introduction to the breadth of chemical engineering through several short-term projects supervised by individual chemical engineering faculty. Areas covered include fluid mechanics, separations, catalysis, and materials properties. Not offered 2000–2001.

ChE 63 ab. Chemical Engineering Thermodynamics. *9 units (3-0-6); first, second terms.* A comprehensive course in classical thermodynamics with engineering and chemical applications. First and second laws; 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 membrane equilibria. Chemical reaction equilibria. Thermodynamics of systems under stress or in force fields. Surface thermodynamics. Instructor: Giapis.

ChE 64. Principles of Chemical Engineering. *9 units (3-0-6); third term. Prerequisite: ChE 63 ab.* Material and energy balances, including recycle processes. Elements of chemical kinetics and chemical reactors. Ideal and nonideal reactors. Instructor: Arnold.

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); second, third terms. Prerequisite: ChE 126 a.* A research project carried out under the direction of a chemical engineering faculty member. A grade will not be assigned to ChE 90 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. Instructor: Gavalas.

ChE 103 abc. Transport Phenomena. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 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, Seinfeld.

ChE 104. Separation Processes. *9 units (3-0-6); first term. Prerequisites: ChE 103 abc, ChE 63 ab.* Equilibrium stage separations, including distillation, absorption, and extraction. Rate-based separations, including chromatography and membrane separations. Instructor: Gavalas.

ChE 105. Process Control. *9 units (3-0-6); first term. Prerequisite: ACM 95/100 abc or concurrent registration.* Review of Laplace transforms and linear algebra. Feedback control of linear systems. Frequency response. Sampled-data systems. Introduction to multivariable control. Instructor: Staff.

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; flowsheets 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: Wagner.

ChE 126 ab. Chemical Engineering Laboratory. *9 units (1-6-2); first, second terms. Prerequisites: ChE 101, ChE 103 abc, and ChE 105, or concurrent registration.* Projects illustrative of problems in transport phenomena, unit operations, chemical kinetics, process control, and reactor design are performed, with special emphasis on oral and written presentation of scientific results. Instructors: Flagan, Davis.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *6 units (4-0-2).* For course description, see Chemistry.

Env/ChE 142 ab. Chemistry of Natural Water Systems. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

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. Prerequisites: Ch/ChE 147 or with 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. Topics include characterization, scaling, and dynamics of polymers in solutions and melts; polymer-polymer thermodynamics in blends and block-copolymers; rubber elasticity; the rubber-glass transition; crystallization and morphology of semi-crystalline polymers. Not offered 2000–2001.

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 64 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: Davis.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6); third term.* Discussion of homogeneous and heterogeneous catalytic reactions, with emphasis on mechanistic principles and on the relationships between the two areas. Topics include homogeneous hydrogenation; catalysis by metals; homogeneous oxidation; catalysis by metal oxides; acid-base catalysis and zeolites. Not offered 2000–2001.

ChE/Env 157. Sources and Control of Air Pollution. *9 units (3-0-6); third term. Open to graduate students and seniors with instructor's permission.* Principles necessary to understanding the sources and control of air pollutants; generation of pollutants in combustion systems; control techniques for particulate and gaseous pollutants; solution of large-scale regional air pollution control problems. Not offered 2000–2001.

ChE/Env 158. Aerosol Physics and Chemistry. *9 units (3-3-3); second term. Open to graduate students and to 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: Flagan.

ChE/Env 159. Atmospheric Chemistry and Physics of Air Pollution. *9 units (3-0-6); second term. Open to graduate students and seniors with instructor's permission.* Principles necessary to understanding the atmospheric behavior of air pollutants; atmospheric gas- and aqueous-phase chemistry; atmospheric diffusion; removal processes and residence times; statistical distributions of pollutant concentrations. Instructor: Cass.

ChE 163. Biocatalysis and Protein Technology. *9 units (3-0-6); second term. Prerequisites: ChE 64, Bi/Ch 110, or instructor's permission.* Biochemical engineering and industrial biotechnology, including biocatalysis and fermentation processes, enzyme kinetics, proetin engineering, special topics in protein evolution. Instructor: Arnold.

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; derivation of various ensembles; statistical fluctuations; connection to thermodynamics; noninteracting quantum and classical gases; heat capacity of solids; adsorption; chemical equilibria; phase transitions; linear response theory; classical fluids; computer simulation methods. Instructor: Wang.

ChE 165. Chemical Thermodynamics. *9 units (3-0-6); first term. Prerequisite: ChE 63 ab or equivalent.* Review of first and second laws and engineering applications. Intermolecular forces and virial coefficients. Equations of state and thermodynamic properties of pure substances. Thermodynamics of gaseous and liquid mixtures. Theories of solutions. Phase and chemical equilibria. Interfacial thermodynamics. Electrolysis and polymeric liquids. Instructor: Wang.

ChE 174. Special Topics in Transport Phenomena. *9 units (3-0-6); third term. Prerequisite: 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; 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, Beauchamp, Tirrell. Additional information concerning this course can be found at http://www.cco.caltech.edu/~chem1/.

Ch 3 a. Fundamental Techniques of Experimental Chemistry. *6 units; 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. Enrollment first term will be limited to students who have gained advanced placement into Ch 41 or Ch 21, or by permission of the instructor. Graded pass/fail. Instructors: Staff.

Ch 3 b. Experimental Procedures of Synthetic Chemistry. *8 units (1-6-1); first term. Prerequisites: Ch 1 a, Ch 1 b, and Ch 3 a.* Instruction in fundamental synthesis, separation, and characterization procedures used in chemical research. Graded pass/fail. Instructors: Staff.

Ch 4 ab. Synthesis and Analysis of Organic and Inorganic Compounds. *9 units (1-6-2). Prerequisite: 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, first and third terms; Ch 4 b, second term only. Instructors: Staff.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. *9 units (1-6-2); first, third terms. Prerequisite: Ch 4 ab.* Modern synthetic chemistry. Specific experiments may change from year to year. Multistep syntheses of natural products, coordination complexes, and organometallic complexes will be included. Experiments to illustrate the fundamental principles of inorganic and organometallic chemistry. Methodology will include advanced techniques of synthesis and instrumental characterization. Instructors: Peters, Grubbs.

Ch 6 ab. Application of Physical Methods to Chemical Problems. *10 units (0-6-4); second, third terms. Prerequisites: Ch 1, Ch 4 ab, and Ch 21 or equivalents (may be taken concurrently).* Introduction to the application of modern physical methods to chemical problems, with emphasis in the area of molecular spectroscopy. Techniques including X-ray crystallography, laser Raman spectroscopy, microwave spectroscopy, electron spin resonance, ultraviolet photoelectron spectroscopy, and Fourier transform ion cyclotron resonance spectroscopy are used to examine the structure, properties, and reaction dynamics of molecules in the gas phase, in solution, and at surfaces. Instructors: Okumura, Beauchamp.

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 permission of instructor. 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: Dervan.

Ch 10 abc. Frontiers in Chemistry. *3 units (2-0-1); first, second terms. 6 units (1-4-1); 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 permission of instructor.* 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, intro-

ductory 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: Lewis, Dougherty.

Ch 14. Chemical Equilibrium and Analysis. *6 units (2-0-4); first 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, Anson.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); first term. Prerequisites: Ch 1 ab, Ch 3 a, Ch 14 (may be taken concurrently).* Laboratory experiments are used to illustrate modern instrumental techniques that are currently employed in industrial and academic research. Emphasis is on determinations of chemical composition, measurement of equilibrium constants, evaluation of rates of chemical reactions, and trace-metal analysis. Instructors: Anson, staff.

Ch 21 abc. The Physical Description of Chemical Systems. *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, Blake, Beauchamp.

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.* Fundamental physical chemistry, with emphasis on those topics most important in biology. Thermodynamics and its applications to aqueous solutions and living systems, membrane potentials and the thermodynamics of transport, reaction kinetics and mechanisms, transport properties, applications of molecular spectroscopy in biology, and statistical mechanics with applications to biological polymers. Instructors: R. Roberts, Rees.

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: Grubbs, Dervan, Dougherty.

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 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. Instructor: Bikle.

Ch 91. Scientific Writing. *3 units (1-0-2); third term.* Practical training in the writing of technical reports, reviews, and research papers on chemical topics. Open to undergraduates only. Graded pass/fail. Not offered 2000–2001.

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 41 abc or equivalent.* Introduction to group theory, ligand field theory, and bonding in coordination complexes and organotransition metal compounds. Systematics of synthesis, bonding, and reactivities of commonly encountered classes of transition metal compounds. Instructors: Bercaw, Peters.

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. Instructors: Lewis, Anson, Freund.

Ch 120 abc. Nature of the Chemical Bond. *Part a, 9 units (3-0-6) first term; Part b, 6 units (2-0-4) second term; Part c, 6 units (1-1-4), third term. Prerequisites: General exposure to quantum mechanics (e.g., Ph 2 ab, Ph 12 abc, or equivalent).* Modern ideas of chemical bonding, with an emphasis on qualitative concepts and how they are used to make 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). The emphasis is on explaining chemical, mechanical, electrical, and thermal properties of materials in terms of atomistic concepts. Part b: The quantum mechanical basis for understanding transition metal systems with a focus on chemical reactivity. There will be an emphasis on organometallic complexes, on homogeneous catalysis, and on heterogeneous catalysis. Part c: The student does an individual research project using modern quantum chemistry computer programs to calculate wavefunctions, structures, and properties of real molecules. Part b not offered 2000–2001. Instructor: Goddard.

Ch 121 ab. Atomic Level Simulations of Materials and Molecules. *Part a, 9 units (3-1-5) second term; Part b, 9 units (3-1-5) third term. Prerequisites: Ma 2 ab, Ph 2 ab, Ch 1 ab, or equivalent. Recommended: Ch 41 abc, Ch 21 a.* Methods for predicting the structures and properties of molecules and solids. The course will highlight theoretical foundations and applications to current problems in: 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); and organometallics and catalysis (heterogeneous and homogeneous). Both terms will involve the use of computers for building and calculating systems of interest. Part a covers the basic methods. Part b will focus on simulations applied to problems in petroleum chemistry. Ch 120 a is recommended but not required for Ch 121 a. Instructor: Goddard.

Ch 122 abc. Methods for the Determination of the Structure of Molecules. *9 units (3-0-6); first, third terms. Prerequisite: Ch 21 abc or instructor's permission.* Modern methods used in the determination of the structure of molecules, including X-ray, electron, and neutron diffraction; mass spectrometry; optical, infrared, Raman, microwave, Mössbauer, nuclear magnetic, and electron spin resonance spectroscopy. The emphasis will be on nuclear magnetic resonance (first term), and diffraction methods and mass spectrometry (third term). All three terms can be taken independently. Ch 122 a will be offered first term. Instructor: Day. Ch 122 bc not offered 2000–2001.

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, Weitekamp.

Ch 126. Molecular Spectra and Molecular Structure. *9 units (3-0-6); third term. Prerequisite: Ch 21 and Ch 125 a taken concurrently, or permission of instructor.* 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 2000–2001.

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.

Ch 130. Spectroscopy. *9 units (3-0-6); third term.* Discussion of various topics in lasers and their applications. Group theory with applications to molecular structure and spectroscopy will also be discussed. Instructor: Zewail.

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, third term; part b, second term. Prerequisites: Ch 21 abc and Ch 41 abc, or equivalent, or consent of instructor.* 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. Instructor: Kuppermann. Ch 135 a not offered 2000–2001.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *6 units (4-0-2); second, third terms. Prerequisite: APh 9 or permission of instructor.* 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. The course will meet for four one-hour lectures per week and will be in a tutorial format with instruction predominantly from graduate students and postdoctoral fellows with expertise in the field. Given in alternate years. Instructor: Lewis.

Ch 142. Frontiers in Chemical Biology. *4 units (2-0-2); second term. Prerequisite: Bi/Ch 110 or instructor's permission.* A discussion of enzyme structure and function, and ligand-protein-nucleic acid interactions. Not offered 2000–2001.

Ch 143. Basic FT NMR Spectroscopy. *9 units (3-2-4); second term. Prerequisite: Ch 41 abc.* 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* video-disc-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. Instructor: Hwang.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 41 abc or equivalent.* An advanced survey of modern organic chemistry. First term: structural and theoretical organic chemistry; kinetic, thermochemical, and orbital symmetry concepts. Second term: organic reaction chemistry emphasizing modern studies of reactive intermediates. Not offered 2000–2001.

Ch 145. Bioorganic Chemistry of Proteins. *9 units (3-0-6); first term. Prerequisites: Ch 41 abc and Bi/Ch 110.* This course aims to define the information that can be derived on the structure and function of enzymes through the use of affinity labeling reagents, mechanism-based inactivators, and transition-state analog inhibitors. While the focus will be on selected classes of enzymes, the material covered is intended to give insight into general rules for the investigation of enzyme mechanisms and inhibitor design. Instructor: Hsieh-Wilson.

Ch 146. Bioorganic Chemistry of Nucleic Acids. *9 units (3-0-6); third term. Prerequisite: Ch 41 ab.* 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 such as 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) will be discussed. Given in alternate years; not offered 2000–2001.

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. Not offered 2000–2001.

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, Peters.

Ch 154. Organometallic Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 112 or equivalent.* A general discussion of the reaction mechanisms, and synthetic and catalytic uses of transition metal organometallic compounds. Instructor: Bercaw.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 163. Lectures-Seminars in Physical Chemistry. *6 units (2-0-4); second term. Prerequisites: None.* Topic will be "Electron Transfer Reactions in Chemistry and Biology." For further description, see Ch 221.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 165. 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. Principles of Three-Dimensional Protein Structure. *9 units (3-3-3).* For course description, see Biochemistry and Molecular Biophysics.

Env/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Env/Ge/Ch 172. Atmospheric Chemistry II. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Env/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Ch 180. Chemical Research. *Units by arrangement. Offered to M.S. candidates in chemistry.* Graded pass/fail.

Bi/Ch 202 abc. Biochemistry Seminar. *1 unit.* For course description, see Biology.

Ch 212. Bioinorganic Chemistry. *9 units (3-0-6); first, third terms. 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. Given in alternate years; offered 2000–2001. Instructor: Barton.

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 and staff.

Ch 221. Electron Transfer Reactions in Chemistry and Biology. *6 units; second term. Prerequisite: Ch 21 abc.* Fundamentals of electron transfer reactions. Molecular (statistical) theory, dielectric continua,

electronic matrix elements, Franck-Condon principle, relevant thermodynamics, reorganization energy, quantum effects, charge transfer spectra, solvent dynamics. Reactions in solution, at metal electrode-liquid, modified electrode-liquid, semiconductor electrode-liquid, and liquid-liquid interfaces. STM theory. Reactions in photosynthetic reaction centers and in other proteins. Given in alternate years; offered 2000–2001. Instructor: Marcus.

Ch 224. Advanced Topics in Magnetic Resonance. *9 units (2-0-7); third term. Prerequisites: Ch 125 abc or Ph 125 abc or concurrent registration or equivalent, Ch 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 developments, 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 first 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. Not offered 2000–2001. Instructor: Staff.

Ch 228. The Dynamics of the Chemical Bond. *9 units (3-0-6); third term. Prerequisite: Ch 21 abc.* Fundamentals of time-dependent phenomena will be discussed with particular focus on the primary processes important to molecular reaction dynamics. Topics such as reaction dynamics, nonradiative decay, coherence, energy redistribution, and wave packet dynamics will be covered. 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 reaction; 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. Instructor: Parker.

Ch 242 ab. Chemical Synthesis. *9 units (3-0-6); first, second terms. Prerequisite: Ch 41 abc.* An integrated approach to synthetic problem solving featuring an extensive review of modern synthetic reactions with concurrent development of strategies for synthesis design. Part a will focus on the application of modern methods of stereocontrol in the construction of stereochemically complex acyclic systems. Part b will focus on strategies and reactions for the synthesis of cyclic systems. Part c is an intensive development of the tools of mechanistic problem solving in organic chemistry and their application to problems in chemical synthesis. Instructors: Stoltz, MacMillan.

Ch 244 a. Topics in Chemical Biology. *9 units (3-0-3); first term.* Current topics at the interface of chemistry and biology. Not offered 2000–2001. Instructor: R. Roberts.

Ch 247 a. 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 2000–2001.

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: AM 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. Instructor: Carlson.

CE 95. Introduction to Soil Mechanics. *9 units (2-3-4); second term. Prerequisite: AM 35 ab.* A general introduction to the physical and engineering properties of soil, including origin, classification and identification methods, permeability, seepage, consolidation, settlement, slope stability, and lateral pressures and bearing capacity of footings. Standard laboratory soil tests will be performed. Not offered every year.

ME/CE 96. Mechanical Engineering Laboratory. *6 or 9 units as arranged with instructor.* For course description, see Mechanical Engineering.

CE/ME 97. Fluid Mechanics Laboratory. *6–9 units as arranged with instructor; third term. Prerequisite: ME 19 ab.* A laboratory course in the basic mechanics of incompressible fluid flow, complementing lecture course ME 19 abc. Students usually select approximately three regular experiments, but they may propose special investigations of brief research projects of their own. Students also gain experience in making engineering reports. Although the course is primarily for undergradu-

ates, first-year graduate students who have not had an equivalent course can take it under CE 100. Instructor: Raichlen.

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 Aeronautics.

Ae/AM/CE 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aeronautics.

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 every year.

CE 110. Analysis and Design of Hydraulic Projects. *6 or more units as arranged; any term. Prerequisite: ME 19 abc.* The detailed analysis or design of a complex hydraulic structure or water resources project emphasizing interrelationships of various components, with applications of fluid mechanics and/or hydrology. Students generally work on a single problem for the entire term, with frequent consultations with their instructor. Instructors: Staff.

CE 113 ab. Coastal Engineering. *9 units (3-0-6); first, second terms. Prerequisites: ME 19 abc and CE 111 or equivalents; ACM 95/100 abc.* Engineering applications of the theory of small and finite amplitude water waves; diffraction, reflection, refraction; wind-generated waves and wave prediction procedures; tides and their interaction with the coastline; effect of waves on coastal structures such as breakwaters and pile-supported structures; coastal processes. Instructor: Raichlen.

CE 115 ab. Soil Mechanics. *9 units (3-0-6); first term. 9 units (2-3-4); second term. Prerequisite: instructor's permission.* Study of the engineering behavior of soil through examination of its chemical, physical, and mechanical properties. Classification and identification of soils, surface chemistry of clays, interparticle reactions, soil structure. Linear constitutive relations for soils, including steady-state and transient water flow. Second term: nonlinear soil behavior, theories of yielding, plasticity, constitutive models, and problems of plastic stability. Failure modes of footings, walls, and slopes. Not offered every year.

CE 124. Special Problems in Structures. *9 units (3-0-6); any term.* Selected topics in structural mechanics and advanced strength of materials to meet the needs of first-year graduate students. Instructors: Staff.

CE 130 abc. Civil Engineering Seminar. *1 unit (1-0-0); 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.

CE 150. Foundation Engineering. *9 units (3-0-6); third term. Prerequisite: CE 115 ab.* Methods of subsoil exploration. Study of types and methods of design and construction of foundations for structures, including single and combined footings, mats, piles, caissons, retaining walls, cofferdams, and methods of underpinning. Text: *Foundation Analysis*, Scott. Not offered every year.

CE 160 abc. Structural and Earthquake Engineering. *9 units (3-0-6); first, second, third terms. Prerequisite: CE 90 or equivalent.* Topics forming the foundation for structural analysis and design are covered. Techniques for linear and nonlinear, static and dynamic analysis, including analysis of structure-foundation and structure-fluid systems, the nature of loadings due to wind and earthquake, concepts in design. Special consideration is given to behavior and design of specific structural systems such as buildings, bridges, concrete dams, liquid-storage tanks, tunnels and pipelines, cable structures, and offshore structures. Special emphasis on engineering for earthquakes. Instructor: Hall.

CE 180. Experimental Methods in Earthquake Engineering. *9 units (1-5-3); third term. Prerequisite: AM 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. Instructor: Hushmand.

CE/Ge 181. Engineering Seismology. *9 units (3-0-6); second term.* Characteristics of potentially destructive earthquakes from the engineering point of view. Determination of location and size of earthquakes; magnitude, intensity, frequency of occurrence; engineering implications of geological phenomena, including earthquake mechanisms, faulting, fault slippage, and effects of local geology on earthquake ground motion. 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.

CE 201. Advanced Work in Structural Engineering.

CE 202. Advanced Work in Soil Mechanics.

CE 203. Advanced Work in Hydraulic Engineering. *Units to be based upon work done; any term.* Special course to meet the needs of advanced graduate students.

ES/CE 204 abc. Hydrodynamics of Free Surface Flows. *9 units (3-0-6).* For course description, see Engineering Science.

CE 210 ab. Hydrodynamics of Sediment Transport. *9 units (3-0-6); second, third terms. Prerequisites: ACM 95/100 abc, Env 112 abc, and CE 101 abc.* The mechanics of the entrainment, transportation, and deposition of solid particles by turbulent fluids, including discussion and interpretation of results of laboratory and field studies of alluvial streams, and wind erosion. Not offered every year.

CE 211. Advanced Hydraulics Seminar. *4 units (2-0-2); every term.* A seminar course for advanced graduate students to discuss and review the recent technical literature in hydraulics and fluid mechanics. Civil and environmental engineering topics that are not available in courses offered by the Division of Engineering and Applied Science. Subject will vary depending upon the needs and interests of the students. May be taken any number of times with the permission of the instructor. Instructors: Staff.

CE 212. Advanced Hydraulics Laboratory. *6 or more units as arranged; any term. Prerequisite: instructor's permission.* A laboratory course, primarily for first-year graduate students, dealing with flow in open channels, sedimentation, waves, hydraulic structures, hydraulic machinery, or other phases of hydraulics of special interest. Students may perform one comprehensive experiment or several shorter ones. Instructors: Staff.

CE 213. Advanced Coastal Engineering. *9 units (3-0-6); third term. Prerequisites: CE 101 abc and CE 113 ab.* Selected topics in coastal engineering such as harbor resonance, mooring and berthing of ships, and structural forces due to waves, tsunamis, and other impulsive wave systems. Not offered every year.

Ae/AM/CE 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aeronautics.

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.

For courses in Environmental Engineering Science, see that section.

CNS 100. Introduction to Computation and Neural Systems. *3 units (3-0-0); second term.* This course is designed to introduce first-year CNS students and the campuswide CNS community 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/Bi 120. The Neuronal Basis of Consciousness. *9 units (4-0-5); second 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.
Given in alternate years; offered 2000–2001. For more information, see http://klab.caltech.edu/cns120/.

CNS/EE 124. Pattern Recognition. *9 units (3-0-6); third term. Prerequisite: Ma 2 or equivalent.* An introduction to pattern recognition from a fundamental mathematical and statistical viewpoint with an emphasis on classic results in the field from the 1950s to the present. Methods and techniques discussed will include optimal Bayesian discrimination, discriminant functions, basic principles of estimation, linear discriminants (including Fisher's method and the perceptron), parametric models such as multivariate Gaussian classifiers, mixture and kernel density methods, nearest neighbor classifiers, feedforward neural network models, decision tree methods, as well as general techniques for unsupervised learning (clustering), dimensionality reduction, and performance estimation such as cross-validation. Instructors: To be announced. Not offered 2000–2001.

EE/CNS 148. Selected Topics of Computational Vision. *9 units (3-0-6).* For course description, see Electrical Engineering.

Bi/CNS 150. Neurobiology. *10 units (4-0-6).* For course description, see Biology.

Bi/CNS 157. Comparative Nervous Systems. *9 units (2-3-4).* For course description, see Biology.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6).* For course description, see Biology.

Bi/CNS 161. Cellular and Molecular Neurobiology Laboratory. *9 units (0-9-0).* For course description, see Biology.

Bi/CNS 162. Central Nervous System Laboratory. *12 units (2-7-3).* For course description, see Biology.

Bi/CNS 163. Sleep and Dreams. *10 units (2-7-1).* For course description, see Biology.

Bi/CNS 169. Methods in Computational Molecular and Cellular Biology. *12 units (3-7-2).* For course description, see Biology.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

CNS/Bi 172. Clinical Neuropsychology. *6 units (3-0-3); second term. Prerequisite: Bi 150 or instructor's consent.* Lecture course discussing the relationship between cerebral cortex and behavior, in particular, with respect to the clinical literature. Cerebral functions are considered in light of acquired behavioral deficits such as aphasia, apraxia, agnosia, callosal syndrome (split-brain), hemineglect, dementia, amnesia, and anosognosia. Instructor: Bogen.

CS/CNS 173. Global Illumination 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/Ph 175. Artificial Life. *9 units (3-0-6); first term. Prerequisites: Ph 12 or equivalent; programming skills.* Introduction to the study of simple living systems using the paradigm of self-replicating code evolving in a noisy environment replete with information, implemented on a computer. Applications to the evolution of complexity, adaptive computation, self-organized criticality, thermodynamical and statistical theories of evolution, population biology, and the "directed" mutation hypothesis. Instructor: Adami.

CNS/Bi 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/CDS 177. Special Topics in Computation and Neural Systems and Control and Dynamical Systems. *Units to be arranged; first, second, or third terms.* Students may register with permission of the responsible faculty member.

CNS 179. Reading in Computation and Neural Systems. *Units by arrangement; first, second, third terms. Permission of instructor required.*

CNS 180. Research in Computation and Neural Systems. *Units by arrangement with faculty. Offered to precandidacy students.*

CNS/Bi/Ph 185. Collective Computation. *12 units (3-1-8); first term. Background: EE 14 and CS 10 or equivalent.* Model neural networks; differential equations and circuits for a neural net; energy functions that compute; associative memory, backpropagation, sequences; systems that learn; self-organizing maps and development; spike-based computing, spikes, coding, information and optimal decision theory; linear and nonlinear visual filtering; processing in cortical networks. Course work includes some hardware laboratory and work in the CNS simulation facility. Instructors: Koch, Psaltis. For more information, see http://www.klab.caltech.edu/cns185/.

CNS/Bi/EE 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4); second term.* Lecture, laboratory, and discussion 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, analog VLSI circuits). The course will focus on early vision processes, in particular motion analysis, binocular stereo, brightness, color and texture analysis, and boundary detection. Students will be required to hand in approximately three homeworks as well as complete one project (mathematical analysis, computer modeling, psychophysics, or hardware implementation). Instructors: Quartz, Shimojo, Cowie. Given in alternate years; not offered 2000–2001. For more information, see http://www.klab.caltech.edu/cns186/.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6); first term.* 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: Winfree.

CNS/CS/EE 188 ab. Computation Theory and Neural Systems. *9 units (3-0-6); second, third terms. Prerequisite: Ma 2.* Introduction to computational models and methods that are inspired by, and related to, neural systems as well as relevant mathematical techniques developed in computer science and engineering. Specific topics include: computing with circuits, feedback and computation, associative memories, analog computing, fault tolerance, learning and elements of parallel and distributed computing. Instructor: Bruck. Additional information concerning this course can be found at http://paradise.caltech.edu/cns188/.

CS/CNS/Bi 191. Molecular Computation. *9 units (3-0-6).* For course description, see Computer Science.

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.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5); third term. Prerequisites: Bi/CNS 150, CNS 185; or instructor's consent.* 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 is information 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 primate cortex. Students are required to hand in three homeworks, discuss one set of papers in class, and participate in the debates. Instructor: Koch.

CNS/Bi 246. Multicellular Recording. *9 units (2-6-1); third term. Prerequisite: Bi 150 or equivalent.* Laboratory course in techniques and applications of multineuron recording in the central nervous system. The course will cover (1) methods for collecting single-cell data, (2) the analysis of multineuron data including spike sorting, and (3) scientific issues addressed by multicellular recording, including population coding and functional connectivity. Students are required to attend a two-hour laboratory lecture/discussion once a week, and complete one project. Multidisciplinary approaches are encouraged that combine engineering principles for data collection and analysis with experimental and theoretical approaches to understanding the nervous system. To this end, students will be encouraged to work in pairs, with one student coming from an engineering laboratory, and one from a neurobiology laboratory. Instructor: Andersen. Not offered 2000–2001.

CNS/Bi 247. Cerebral Cortex. *6 units (2-0-4); second term. Prerequisite: Bi 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.

CNS/EE 248. Sensory Information Processing Laboratory. *12 units (1-2-9); third term. Prerequisite: any of CNS/EE 124, CNS 186, EE/CNS 148 or equivalent.* Laboratory course in real-time applications of sensory processing. Students will be guided through the construction of working systems performing recognition, tracking, and navigation using vision, audition, and other sensors. Examples: vehicle navigation, face recognition, signature verification, fingerprint identification, and voice classification. At the beginning of the term a number of lectures will introduce the materials and methods involved in the experiments. Instructors: Psaltis, Perona. Additional information about this course can be found at http://www.cns.caltech.edu/cns248/.

CS/CNS 257 abc. Simulation. *9 units (3-3-3) first; (3-5-1) second; (3-5-1) third term.* For course description, see Computer Science.

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. Special Topics in CNS: Introduction to Mathematical Tools for Theoretical Neuroscience. *12 units (4-0-8); second term. Prerequisite: Ma 1, Ma 2 or equivalent.* A primer on mathematical techniques used in theoretical neuroscience. Linear Algebra: matrices, eigenvalues and eigenvectors, principal component analysis; Fourier transformation: discrete and continuous variables, FFT, filters, convolution; Statistics: random variables, binomial-Gaussian-, Poisson distribution, renewal processes, random walk, correlation functions, powerspectrum; ODE's: solutions, local and global stability, Liapunov function; Information theory: entropy, mutual information; Differential Geometry: vector algebra, div, grad, curl. Exercises in MATLAB. Instructor: Schuster. Not offered in 2000–2001.

CNS 286 b. Learning Systems for Control of Animal-Like Creatures. *12 units (4-4-4); second term.* Lecture course to consist mostly of projects, with a series of lectures on animat research, neural networks, genetic algorithms, and psychology. The purpose of the course is to provide a "systems" view of learning by taking into account all the practical constraints of a system that must undergo changes while it maintains appropriate performance. The course gives students

the opportunity to realize complete learning control architectures with real or simulated animal-like machines (animats). This requires special tools inspired by Steven Grossberg's work and reinforcement learning theory. Instructor: Staff. Not offered in 2000–2001.

CNS/CS/Bi 288. Special Topics Seminar: DNA and Molecular Computation. *6 units (3-0-3); second term.* Students will read, present, and discuss classic and current papers. Topics will address computation where individual molecules are the processing and data storage devices: biochemical networks, DNA-based computers, molecular design, simulations, experimental techniques, physical limits of computation, role of thermal noise. Instructor: Winfree.

COMPUTER SCIENCE

CS 1. Introduction to Computation. *6 units (2-3-1); first term. Prerequisites: none.* CS 1 is an introduction to the foundations of computation. Lectures will include a series on fundamental issues in computer science. Course emphasis is on the techniques of problem analysis and the development of algorithms and programs. Topics will include data structures, abstraction, recursion, iteration, as well as the design and analysis of basic algorithms. The student is expected to do homework assignments in problem solving and program design as well as weekly laboratory assignments to reinforce the lecture material. All students interested in computer science are encouraged to take this course. Instructor: Covington.

CS 2. Introduction to Data Structures and Algorithms. *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: Covington.

CS 3. Structure and Interpretation of Computer Programs. *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; non-determinism; distributed algorithms and data structures. The weekly laboratory exercises allow the students to investigate the lecture material by writing non-trivial applications. Instructor: Covington.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6).* For course description, see Mathematics.

CS 20 abc. Computation, Computers, and Programs. *9 units (3-3-3); first, second, third terms. Prerequisites: CS 2 or equivalent.* This course will focus on the fundamental underpinning of computer science. Topics will include abstract models of computation, the limits of computation, analysis of algorithms, formal languages, automata theory, graph theory, logic, combinatorics, numeric and symbolic computation, and program translation and semantics. Practical examples will be drawn from diverse areas such as computational geometry, numerical analysis, computational logic, and compiler design. Course work will be both theoretical and practical, with assignments involving both proofs and programs. Students will learn to program in languages such as Lisp, Prolog, and Java. Instructor: Arvo. Additional information about this course can be found at http://www.cs.caltech.edu/~cs20/.

CS 40/140 ab. Programming Laboratory. *9 units (1-8-0); second, third terms. Prerequisites: CS 20 or equivalent.* Undergraduates must enroll for CS 40; graduates must enroll for CS 140. This laboratory course is meant to expose students to programming in the large. The lectures cover both object-oriented program design techniques and other methodologies with the goal of demonstrating proper design techniques for large programming projects. These methodologies are then applied to the design and implementation of a significant programming project. This project is of a large enough scale that the students must work in large teams in order to design and implement the system in the two-term course. Throughout the course, students will be expected to present their designs and implementations at scheduled design reviews. The emphasis in the course is not only in achieving the task, but also in properly analyzing the problem space, presenting a clear problem specification, and implementing a modular and a maintainable design. Instructor: George.

CS 47/147. Advanced Object-Oriented Programming. *9 units (3-3-3); first term. Prerequisites: CS 2 and CS 20 or equivalent.* Undergraduates must enroll for CS 47; graduates must enroll for CS 147. This course covers the advanced object-oriented programming techniques typically used in large programming projects. Fundamental programming techniques such as object design, inheritance of implementation and/or interface, and polymorphism are also discussed. Other, more advanced, programming concepts covered include smart pointers, garbage collection, object permanence, patterns, and internet programming. Instructor: George.

EE/CS 51. Principles of Microprocessor Systems. *9 units (3-0-6).* 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. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor.* For course description, see Electrical Engineering.

EE/CS 54. Advanced Microprocessor Projects Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor.* For course description, see Electrical Engineering.

EE/CS 80 abc. Senior Thesis. *9 units.* For course description, see Electrical Engineering.

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. Instructors: Staff.

CS 90. Undergraduate Research in Computer Science. *Units in accordance with work accomplished. Consent of both research adviserand 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. Instructors: Staff.

CS 101 abc. Special Topics in Computer Science. *Units in accordance with work accomplished. Offered by announcement. Prerequisite: CS 20.* The topics covered vary from year to year, depending on the students and staff. Primarily for undergraduates.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6).* For course description, see Mathematics.

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 is information and what is computation; 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: Abu-Mostafa. Not offered 2000–2001.

CS 133. Topics in Symbolic Computation. *9 units (3-3-3); second term. Prerequisites: CS 20 or permission of instructor.* This course will introduce students to a number of topics in symbolic computation including computational logic, mechanical theorem proving, and computer algebra. A number of important concepts from artificial intelligence will also be discussed, such as non-monotonic reasoning, belief revision, and planning. Useful programming techniques such as continuations, nondeterminism, and heuristic search will be covered. Students will gain practical experience by implementing many of the

basic algorithms in Lisp or Prolog, and by completing a term project. Some prior experience with Lisp. Prolog, or predicate calculus is desirable. Instructor: Arvo. Not offered 2000–2001. Additional information concerning this course can be found at http://www.cs.caltech.edu/~cs133/.

CS 134 a. Computing Systems. *9 units (3-3-3); first term. Prerequisites: CS 20 or permission of the instructor.* Operating systems, monolithic and microkernels, virtual machines. Naming, memory management, segmentation, paging, and virtual memory. Filesystems and I/O. Threads, processes, scheduling, locks, semaphores, and mutual exclusion. Security policies, access-control, capabilities, and language-based security. Instructor: Hickey.

CS 134 b. Computing Systems, Compilers, and Languages Laboratory. *12 units (3-6-3); second term. Prerequisites: CS 134 a or permission of the instructor.* Programming models and languages for operating systems. Execution environments, storage management, and operating system interfaces. Binding mechanisms, abstraction, optimization, and code generation. Parsing and lexical analysis. Students will build a working compiler. Instructor: Hickey.

CS 134 c. Advanced Computing Systems. *9 units (3-3-3); third term. Prerequisites: CS 134 b or permission of the instructor.* Programming and computing environments. Parallel and distributed operating systems, cache coherency, virtual network paging, SIMD and MIMD models. Language-based operating systems. Modular kernels, kernel/user abstraction weakening. Naming, distributed security policy, resource management. Mobile code. Execution models for non–Von Neumann machines. Instructor: Hickey.

CS/EE 137 ab. Electronic Design Automation. *9 units (3-3-3); second, third terms. Prerequisite: basic algorithms and computational theory (CS 138), some exposure to VLSI and/or achitecture (CS 181), or permission of the instructor.* Formation, automation, and analysis of design mapping problems, with emphasis on VLSI and computational realizations. Major themes include: formulated and abstracting problems, figures of merit (e.g., energy, delay, throughput, area, mapping time), representation, traditional decomposition of flow (logic optimization, covering, scheduling, retiming, assignment, partitioning, placement, routing), and techniques for solving problems (e.g., greedy, dynamic programming, search, [integer] linear programming, graph algorithms, randomization). This is a two-term sequence. The first term will cover the major intellectual ground and present students a series of contained projects as a chance to exercise their understanding of the material. In the second term, students will work through all the phases of formulation, design, automation, and analysis of some particular automation problem, preferably one that arises in the student's own research. Instructor: DeHon. Not offered 2000–2001.

CS 138 abc. Computer Algorithms. *9 units (3-0-6); first, second, third terms. Prerequisite: CS 20 or equivalent.* Design and analysis of algorithms. Techniques for problems concerning graphs, flows, number theory, string matching, data compression, geometry, linear algebra and coding theory. Optimization, including linear programming. Randomization. Basic complexity theory and cryptography. Instructor: Schulman.

CS 139 abc. Concurrency in Computation. *9 units (3-0-6); first, second, third terms. Prerequisite: CS 20 or equivalent.* 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. Instructor: Martin. Given in alternate years; not offered 2000–2001.

CS 141 abc. Distributed Computation Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisites: CS 20 or equivalent.* 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; not offered 2000–2001.

CS 142 abc. Decision Support Systems. *9 units (3-3-3); first, second, third terms. Prerequisite: Programming experience using PASCAL. Permission of the instructor required.* The building of conceptual models as an expression of the patterns perceived in the analysis of data. Database systems, discrete simulation, decision support systems, and expert systems. Small group projects and extensive use of the computer. Instructor: Thompson. Not offered 2000–2001.

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. Only section a will be offered in 2000–2001.

Bi/CS 164. Projects in Bioinformatics. *9 units (3-3-3); third term.* For course description, see Biology.

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: 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 173. Global Illumination Laboratory. *12 units (3-6-3); second term. Prerequisites: Ma 2 and extensive programming experience. CS/CNS 171 recommended.* This course will concentrate on the theory and efficient algorithms for the solution of the illumination problem based on physical principles. Fundamental algorithms discussed include ray tracing and radiosity methods together with their associated theories: the rendering equation, Monte Carlo sampling methods, and finite element approximations, including hierarchical methods based on wavelets. Extensive implementation exercises are an integral part of this class and solid programming ability is required, though prior exposure to interactive computer graphics techniques is not. Instructor: Barr. Not offered 2000–2001.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3); third term. Prerequisites: Ma 2 and CS/CNS 171 or CS/CNS 173 or CS 175 or permission of instructor.* 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. Instructor: Barr.

CS 175. Topics in Geometric Modeling. *9 units (3-3-3); third term. Prerequisite: permission of instructor.* This course will cover both classical and state-of-the-art approaches to geometric modeling as needed in computer-aided geometric design and graphics. Subjects treated include classical splines and their theory and practice (Bernstein Bezier form, de Casteljau algorithm, knot insertion, polar forms and blossoming, degree elevation) as well as more recent approaches based on subdivision (Chaikin's algorithm, subdivision schemes of Loop, Catmull-Clark, and Butterfly). Both the underlying mathematical theory and its implementation in the form of highly efficient algorithms will be taught. Instructor: Schröder. Not offered 2000–2001.

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. Instructor: Martin. Not offered 2000–2001.

CS/EE 184 abc. Computer Architecture. *9 units (3-3-3); first, second, third terms. Prerequisites: basic digital design (EE 4), basic computability (CS 20), or permission of the instructor.* Organization and design of physical computational systems, basic building blocks for computations, understanding and exploiting structure in computational problems, design space, costs, and tradeoffs in computer organization, common machine abstractions, and implementation/optimization techniques. The course will develop the fundamental issues and tradeoffs 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. Instructor: DeHon. Given in alternate years; offered 2000–2001.

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. Given in alternate years; not offered 2000–2001.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/CS/EE 188 ab. Computation Theory and Neural Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CS/CNS/Bi 191. Molecular Computation. *9 units (3-0-6); second term.* This course investigates computation by molecular systems, emphasizing models of computation based on the underlying physics and chemistry. Topics include computation by self-assembly, molecular folding, signal transduction, genetic regulatory networks, and transcription; biochemical networks; differential and stochastic equations for biochemical systems; equilibrium and non-equilibrium computing; physical limits of computation; reversible computation; DNA-based computers; in-vitro evolution and molecular ecosystems. Instructor: Winfree. Not offered 2000–2001.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

CS 237 abc. Compiler Design Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisite: Advanced programming background.* Current practice and research in programming languages. Syntactic and semantic issues with emphasis on the latter. Syntactic topics: finite automata, regular expressions, and lexical analysis; push-down automata and context-free grammars; top-down and bottom-up parsing techniques; syntax-directed translation. Semantic topics: code generation, optimization, binding mechanisms, storage management, and execution environments. Language design topics: abstraction mechanisms, advanced control regimes, very-high-level languages, functional languages, object-oriented languages, logic programming languages. Further topics: interpreter and compiler construction issues, the impact of languages on hardware design. Extensive laboratory work will be required. Instructor: Hickey. Not offered 2000-2001.

CS/CNS 257 abc. Simulation. *9 units (3-3-3) first; (3-5-1) second; (3-5-1) third term. Permission of the instructor required.* Mathematical and computational modeling methods. First term: the mathematical foundations of simulation, such as Eulerian equations of motion, tensor analysis, applied 3-D geometry, and the mathematics of continuum dynamics. Second term: the numerical methods of simulation, such as the numerical solution of differential equations, the finite element method, and Monte Carlo techniques. Third term: case studies applying these techniques to selected three-dimensional problems in the physical sciences. Term projects for the third term will involve implementing a case study or other computational application of the methods. Some experience with vector and raster graphics would be helpful. Instructor: Barr. Not offered 2000–2001.

CS 274 abc. Topics in Computer Graphics. *9 units (3-3-3); first, second, third terms. Prerequisite: Permission of instructor required.* 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 permission of instructor. Not offered 2000–2001.

CS 280. Research in Computer Science. *Units in accordance with work accomplished. Approval of student's research adviser and his or her option adviser must be obtained before registering.*

CS 282 abc. Reading in Computer Science. *6 units or more by arrangement; first, second, third terms. Permission of the instructor required.*

CS 284 abc. Computer Science Seminar on Mathematics of Program Construction. *9 units (3-0-6); first, second, third terms. Prerequisite: CS 20 or permission of instructor.* This course addresses the mathematical basis of programming. First term: predicate calculus, lattice theory, sequential programming. Second term: relational calculus, programs as trace-sets, temporal properties. Third term: models of concurrency and concurrent programming. Instructors: Staff. Not offered 2000–2001.

CS 286 abc. Seminar in Computer Science. *3, 6, or 9 units, at the instructor's discretion. Permission of the instructor required.*

CNS/CS/Bi 288. Special Topics Seminar: DNA and Molecular Computation. *6 units (3-0-3).* For course description, see Computation and Neural Systems.

CONTROL AND DYNAMICAL SYSTEMS

CDS 110 ab. Introduction to Control of Physical Systems. *9 units (3-0-6); first, second terms. Prerequisite: ACM 95/100 abc.* Application of feedback analysis and design to physical systems, including classical control theory in the frequency and time domains. Stability; performance; methods based on Bode, Nyquist, and root-locus diagrams. Representation in state space. Analog and discrete dynamical systems. Introduction to multivariable control. Instructor: Staff. Additional information concerning this course can be found at http://www.cds.caltech.edu/cds/courses/cds110/.

CDS 111. Applications of Control Technology. *9 units (3-3-3); third term. Prerequisite: CDS 110 or equivalent.* Application of modern control design techniques to physical systems. The goal of this course is to teach students how to design and implement feedback controllers on physical systems, and to allow students to evaluate different control design methodologies on experimental hardware. Instructor: Staff. Additional information concerning this course can be found at http://www.cds.caltech.edu/cds/courses/cds111/.

CDS 140. Introduction to Dynamics. *9 units (3-0-6); first term. Prerequisite: ACM 95/100.* Basic topics in dynamical systems in Euclidean space, including equilibria, stability, Liapunov functions, periodic solutions, Poincaré-Bendixon theory, Poincaré maps. Attractors and structural stability. The Euler-Lagrange equations,

energy as a Liapunov function, conservation laws. Introduction to simple bifurcations; eigenvalue crossing conditions. Discussion of bifurcations in applications. Instructor: Staff. Additional information about this course can be found at http://www.cds.caltech.edu/cds/courses/.

CNS/CDS 177. Special Topics in Computation and Neural Systems and Control and Dynamical Systems. *Units to be arranged.* For course description, see Computation and Neural Systems.

CDS 201. Applied Operator Theory. *9 units (3-0-6); first term. Prerequisite: ACM 95/100 or equivalent.* Invariant subspaces, Jordan form, Cayley-Hamilton theorem, matrix exponential, singular value decomposition, some Banach and Hilbert spaces, operators, duals, adjoints, induced norms, and spectral theory. Calculus in linear spaces, the inverse and implicit function theorems. Instructor: Staff.

CDS 202. Geometry of Nonlinear Systems. *9 units (3-0-6); second term. Prerequisites: 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's theorem. Instructor: Marsden.

CDS 205. Geometric Mechanics. *9 units (3-0-6); third term (alternate years). 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 will include (taught in a course the following year) reduction theory, fluid dynamics, the energy momentum method, geometric phases, bifurcation theory for mechanical systems, and nonholonomic systems. Instructor: Marsden.

CDS 212. Introduction to Modern Control. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 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: Staff.

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, μ analysis

and synthesis, real parametric uncertainty, Kharitonov's theorem, uncertainty modeling. Instructor: Doyle.

CDS 221. Control of Nonlinear Systems. *9 units (3-0-6); third term (alternate years). Prerequisites: CDS 140, CDS 201, CDS 202 or AM 125 a, CDS 212.* Analysis and design of nonlinear control systems using Lyapunov theory and differential geometric methods. Controllability, observability, feedback linearization, invariant distributions, disturbance decoupling. Second-order systems, describing functions, direct and indirect method of Lyapunov, I/O stability, adaptive control. Instructor: Murray.

CDS 224. System Identification. *9 units (3-0-6); third term (alternate years). Prerequisites: CDS 201, CDS 212.* Review of probability, statistics, and stochastic processes. Optimal predictors for input-output and state-space models, nonparametric, prediction-error, and correlation methods. Asymptotic analysis. Computational aspects. Recursive identification. Experiment design. Model validation and closed-loop identification. Instructor: Doyle.

CDS 240. Nonlinear Dynamical Systems and Chaos. *9 units (3-0-6); second term. Prerequisite: CDS 140.* Normal form theory, center manifold theory, codimension two and larger bifurcation theory, normally hyperbolic invariant manifolds, nonlinear resonance, the KAM theorem, method of averaging, symbolic dynamics, the Smale horseshoe, Melnikov's method, homoclinic and heteroclinic orbits, bifurcations. Instructor: Wiggins.

CDS 242. Hamiltonian Dynamics. *9 units (3-0-6); third term (alternate years). Prerequisite: CDS 240.* Hamiltonian stability and bifurcation theory, Poincaré-Birkhoff normal forms, KAM theory, Nekhoroshev theory, Arnold diffusion.

CDS 270. Advanced Topics in Systems and Control. *Hours and units by arrangement.* Topics dependent on class interests and instructor. Can be repeated for credit.

CDS 280. Advanced Topics in Dynamical Systems Theory. *Hours and units by arrangement. Prerequisite: consent of instructor.* 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. Can be repeated for credit.

CDS 300 abc. Research in Control and Dynamical Systems. *Hours and units by arrangement.* Research in the field of control and dynamical systems. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructors: Staff.

CORE

Core 1 ab. Science Writing. *3 units (1 unit for 1 a; 2 units for 1 b); first, second; second, third terms.* Satisfactory completion of this course is required to satisfy the written component of the Science Communications Requirement. Students must complete a 3,000-word paper on some subject in science or engineering, which will be published in the student electronic journal established for this purpose. Completion of 1 a requires submission of a draft of the paper; completion of 1 b requires acceptance of the final version of the paper. Each student will work individually with a faculty member on the writing of the paper. Instructor: Pierce.

ECONOMICS

Ec 11. Introduction to Economics. *9 units (3-0-6); first, third terms.* An introduction to economic methodology, models, and institutions. Includes both basic microeconomics and an introduction to modern approaches to macroeconomic issues. Instructors: Plott, Wilkie.

Ec 13. Readings in Economics. *Units to be determined for the individual by the department. Not available for credit toward humanities–social science requirement.* Graded pass/fail.

EC/SS 20. Oral Presentation. *3 units (2-0-1); second term.* In this course students will present material of their own choosing to other members of the class. The material can come from any field in economics and the social sciences, and can be theoretical or empirical, contemporary or historical. Emphasis will be placed on the optimal organization and delivery of the material. Instructor: Staff

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); second term. 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: Wilkie.

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. Instructor: Dubin.

Ec 118. Environmental Economics. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* The methods of price and welfare theory are used to analyze the causes of air, water, and other environmental pollution, to examine their impact on economic welfare, and to evaluate selected policy alternatives for managing our environment. Instructor: Staff.

Ec 120. International Economic Theory. *9 units (3-0-6).* Factors affecting the exchange of goods and services and the flow of capital between markets. Theory is stressed. Instructor: Staff. Not offered 2000–2001.

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); second term. Prerequisite: Ma 112 a.* The application of statistical techniques to the analysis of economic data. Instructor: Grether.

Ec/SS 128. Economic and Financial Development in the 19th and 20th Centuries. *9 units (3-0-6); second term. Prerequisite: Ec 11 or SS 13.* Economic analysis of financial and industrial development of various regions of the world from 1800 to the present. Topics may include agrarian reform and the end of serfdom; capital markets and financial institutions and their role in industrialization; bank panics, market crashes, and hyperinflation; and the rise and fall of communism in Eastern Europe. Instructor: Staff. Not offered 2000–2001.

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: Davis.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Industrial Revolution. *9 units (3-0-6); first term. 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. Instructor: Hoffman.

Ec 131. Labor Economics. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* Modern theory of labor markets. Uses empirical evidence to supplement theoretical results. Instructor: Staff. Not offered 2000–2001.

PS/Ec 134. The Political Economy of Urban Areas. *9 units (3-0-6).* For course description, see Political Science.

Ec 135. Economics of Uncertainty and Information. *9 units (3-0-6); third term. Prerequisites: Ec 11, Ma 2.* An analysis of the effects of uncertainty and information on economic decisions. Included among the topics are individual and group decision making under uncertainty, expected utility maximization, insurance, financial markets and speculation, product quality and advertisement, and the value of information. Instructor: Ghirardato.

Ec 138. Introduction to Welfare Economics. *9 units (3-0-6). Prerequisite: Ec 11.* Economic efficiency of various market arrangements; modern developments in the theories of decentralization and informational efficiency. Instructors: Staff. Not offered 2000–2001.

Ec 145. Public Finance. *9 units (3-0-6); first term. Prerequisite: Ec 11 or equivalent.* An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Instructor: Staff. Not offered 2000–2001.

BEM/Ec 146. Organization Design. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec 155. Decision Theory. *9 units (3-0-6); third term. Prerequisite: Ma 2.* Course will discuss the formal analysis of individual decision making from normative and descriptive standpoints. Topics to be covered include choice under certainty, under risk (von Neumann and Morgenstern) and under certainty (Anscombe-Aumann and Savage), conditional preferences and probabilities, independence and de Finetti's theorem on exchangeability, dynamic decision making, non-expected utility models, non-additive probabilities, and multiple priors. Instructor: Ghirardato.

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.

Ec 161. Business Cycles. *9 units (3-0-6); third term. Prerequisite: Ec 11.* The role of dynamic decision making in economic fluctuations and growth. Topics include: labor supply decisions and unemployment, behavior of inventories, real investment behavior, productivity, and real capital markets. Instructors: Staff. Not offered 2000–2001.

Ec 162. Monetary Theory. *9 units (3-0-6); second term. Prerequisite: Ec 11.* The role of money and the payments mechanism in the U.S. economy. Topics include: behavior of the Federal Reserve and the commercial banking system, determination of interest rates and the term structure of interest rates, empirical analysis of the demand and supply of money, and financial markets. Instructor: Fohlin.

Ec/BEM 163. Financial Intermediation. *9 units (3-0-6); third term. Prerequisite: Ec 11.* Existence, structure, and regulation of financial intermediaries. Information asymmetry, transactions costs, maturity and liquidity transformation, credit rationing, financial fragility and systemic risk, deposit insurance, regulatory issues, comparative systems. Theoretical foundations and empirical testing. Emphasis on class discussion and development of student research. Instructor: Fohlin.

PS/Ec 172. Noncooperative Games in Social Sciences. *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.

ELECTRICAL ENGINEERING

EE 4. Fundamentals of Digital Systems. *9 units (2-3-4); first term. Three units allowed toward freshman laboratory requirement.* An introduction to modern digital design techniques. Boolean algebra and the formulation of logic equations. Design of combinational and sequential logic circuits using integrated circuits. Multiplexers, ROMs, and programmable logic arrays. State machines. The building blocks of the digital computer: binary arithmetic, the ALU, random access memory, controllers, and sequences. Lab experiments are integrated with the course. Graded pass/fail. Instructor: Goodman.

EE 20 ab. Electronics Laboratory. *9 units (3-3-3); first, second terms. Prerequisites: Ma 1 abc, Ph 1 abc, EE 20 a for EE 20 b.* Fundamentals of electronics through the progressive construction of a radio transceiver—electronic components, phasors, transmission lines, filters, speakers, audio amplifiers, transistors, radio amplifiers, oscillators, mixers, noise, intermodulation, antennas, and propagation. Instructor: Rutledge.

EE 30. Op Amps and Linear Integrated Circuits. *9 units (2-3-4); second term. Prerequisite: EE 20 ab; Ph 5/105 may be used as a prerequisite with the permission of the instructor.* Introduction to operational amplifiers and other linear integrated circuits. Covers op amp internal design from the basic differential amplifier to the 741. Frequency compensation and stability. Op amp application circuits linear and nonlinear such as integrator, differentiator, summer, multiplier, active filters, signal generation. Other linear ICs: current differencing (Norton)

amplifier, 555 timer, phase-locked loop, A/D converter, sample and hold, comparator, voltage controlled oscillator (VCO), voltage regulators. Homeworks and lab experiments integrated with course work. Instructor: Goodman.

EE 32 ab. Signals, Systems, and Transforms. *9 units (3-0-6); first, second terms. Prerequisites: Ma 1, Ma 2, and EE 20 ab.* An introduction to the analysis and synthesis of analog and digital circuits, signals, and systems. Sampling, modulation, and filtering of signals represented as continuous or discrete functions of time. Input-output relations of linear time-invariant systems, state-space representations, and stability analysis. Special emphasis will be placed on transform techniques (Fourier, Laplace, and Z-transforms). Instructor: Abu-Mostafa.

EE 40. Introduction to Sensors and Actuators. *9 units (3-0-6); first term. Prerequisites: Ph 1 abc and EE 20 ab.* 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. A collection of devices that will be discussed include optical sensors, solar cells, CCD, CMOS imager, temperature sensors, magnetic sensors, mechanical sensors, acoustic sensors (microphones), speakers, electrical generators, motors, etc. Instructor: Tai.

EE 50. Advanced Digital Design. *9 units (3-0-6); first term. Prerequisite: EE 4 or EE/CS 52.* Advanced digital design as it applies to the design of ASICs, in particular gate arrays and standard cells. The course covers both design and implementation details for various logic device technologies with emphasis on the practical aspects of ASIC design such as timing, testing, and fault grading. Topics include synchronous design, state machine design, design for testability, PALs, FPGAs, standard cells, timing considerations, fault vectors, and fault grading. Instructor: George.

EE/CS 51. Principles of Microprocessor Systems. *9 units (3-0-6); second 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 to hardware, in assembly language. Instructor: George.

EE/CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0); third 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 to analog systems, and programming microprocessors in high-level languages. Instructor: George.

EE/CS 53 abc. Microprocessor Project Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor; first, second, third terms. Prerequisite: EE/CS 52 or equivalent. If this course is used to satisfy part of the senior design project requirement, it must be taken as a 12-unit course.* 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.

EE/CS 54 abc. Advanced Microprocessor Projects Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor; first, second, third terms. Prerequisite: permission of instructor.* A project laboratory to permit the student to design and build a microprocessor-based system of significant complexity. The student must propose, design, implement, and document a project which uses microprocessors and includes a significant hardware and/or software component. The laboratory is for the experienced student who can work independently and who has taken or has had experience equivalent to EE/CS 53. Instructor: George.

EE 55 abc. Advanced Digital Design Laboratory. *9 units (0-9-0); first, second, third terms. Prerequisite: EE 50.* This laboratory affords the student the opportunity to apply the digital design techniques learned in EE 50 to the design of a large ASIC. The student is expected to propose, design, and test a digital system with a significant amount of complexity. This system will be implemented and tested in either FPGAs, standard cell, or gate arrays. Instructor: George.

EE/CS 80 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisites: permission of instructor, 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 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 20 ab.* A structured laboratory course which 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. Text: Literature references. Instructor: Megdal.

EE 91 ab. Experimental Projects in Electronic Circuits. *Units by arrangement; first, second terms. 12 units minimum each term. Prerequisites: EE 20 ab. Recommended: EE/CS 51 and 52, and EE 114 ab (may be taken concurrently). Open to seniors; others only with consent of instructor.* 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. Application-Specific Computers. *9 units (3-3-3); third term. Prerequisite: EE 50 or CS/EE 181 a.* This class studies computer architecture and the design of application-specific processors. After covering the general principles of generic CPU design, the class investigates the design of processors specialized to specific applications such as string processing, binary programming, digital signal processing, and machine control. There is significant laboratory work in the course in which the students are expected to design and implement processors discussed in the class using FPGAs. Instructor: George. Not offered 2000–2001.

EE/Mu 107 abc. Projects in Music and Science. *Units to be individually arranged, up to a maximum of 12.* Students will carry out, singly or in groups, projects of study or research exploring the connections of music with the sciences. EE/Mu 107 a will be devoted to Analytic Listening to Live and Reproduced Sound; it may be taken by itself and has no prerequisites. *EE/Mu 107 b and c, devoted to the projects, require instructor's permission.* Projects may be done for joint credit with EE 91 if approved by both instructors. EE/Mu 107 projects may be continued into a second year. Instructor: Boyk. Additional information concerning this course can be found at http://www.cco.caltech.edu/~musiclab and http://www.cco.caltech.edu/~boyk.

EE 112 abc. Digital Signal Processing. *9 units (3-0-6); first, second, third terms. Prerequisites: EE 32 ab or equivalent.* Discrete time signals and systems, classical filter approximations, IIR digital filters, optimal FIR filters, linear-phase filters, digital filter structures, stability test, FFT and fast convolutions, allpass filters and applications, cascaded lattice structures, state-space descriptions, finite-precision effects, limit cycles and their suppression, low-sensitivity structures, and roundoff noise and its minimization in digital filters. Multirate digital signal processing, decimation and interpolation of data, efficient polyphase structures, Nyquist filtering, filter banks, subband coders, orthonormal signal basis, principal component filter banks, wavelet transforms, and unconventional ways of sampling a signal. Optimal quantization, bit-allocation, optimal subband coders and transform coders for data compression, discrete-time Karhunen-Loeve transforms, and discrete cosine transform (DCT). Linear predictive coding and applications, detection of sinewaves in noise, theoretical data compression bounds (rate-distortion), autoregressive modeling, and differential coding

(DPCM) of signals. Applications are drawn from signal compression, digital audio, speech, signal-detection, and digital communications. Instructor: Vaidyanathan.

EE 114. 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. Instructor: Hajimiri.

a. Analog Circuit Design. *9 units (3-0-6); first term. Prerequisite: EE 20 ab or equivalent.* Deals with continuous time and amplitude signals. Covers the 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.

b. Analog Circuit Design. *9 units (3-0-6); second term. Prerequisite: EE 114 a or equivalent.* 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.

CNS/EE 124. Pattern Recognition. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

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 multi-terminal networks. Discussion of philosophical and practical implications of the theory. This course, when combined with EE 112 abc, EE/Ma 127 ab, 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 127 abc. Error-Correcting Codes. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 2.* This course, which is a sequel to EE/Ma 126 a, but which may be taken independently, will develop from first principles the theory and practical implementation of the most important techniques for combatting 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); convolutional codes;

and concatenated coding systems. Emphasis will be placed on the associated encoding and decoding algorithms, and students will be asked to demonstrate their understanding of these algorithms with software projects. In the third term, the modern theory of "turbo" and related codes (e.g., regular and irregula LDPC codes), with suboptimal iterative decoding based on belief propagation, will be presented. Instructor: McEliece.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first and second terms; (1-4-4) third term.* For course description, see Computer Science.

APh/EE 130 abc. Introduction to Optoelectronics and Optoelectronic Devices. *9 units (3-0-6).* For course description, see Applied Physics.

APh/EE 132. Fourier Optics. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 137 ab. Electronic Design Automation. *9 units (3-3-3).* For course description, see Computer Science.

EE 141. Swarm Intelligence. *9 units (2-4-3); second term. Prerequisites: Ma 2, Ph 1, CS 1.* Swarm intelligence is a new computational and behavioral metaphor for solving distributed problems; it is based on the principles underlying the behavior of natural systems consisting of many individuals, such as ant colonies and bird flocks. The approach emphasizes distributedness, direct or indirect interactions among relatively simple but autonomous individuals, flexibility, and robustness. Applications include optimization algorithms, telecommunication and VLSI routing, and autonomous collective robotics. In this course, we will study natural systems exhibiting swarm intelligence, and apply their principles to the control of simulated and real collective autonomous robots of different sizes (from 2 cm to 30 cm in diameter) and capabilities (from PIC-based to PC104-based Linux architechtures). Weekly labs and a final 3-week project are integral components of the course. Instructors: Martinoli, Holland, Goodman.

Ay/EE 144. Imaging at Radio, Infrared, and Optical Wavelengths by Interferometric and Adaptive Techniques. *9 units (3-0-6).* For course description, see Astronomy.

EE/CNS 148. Selected Topics of Computational Vision. *9 units (3-0-6); third term. Prerequisites: Familiarity with basic calculus, linear algebra, and geometry. Some proficiency in computer programming.* The focus is on three-dimensional vision: motion analysis, shape recovery and recognition, vision-based navigation, attention. There will be 2–4 homework assignments, including computer simulations and a final project on a vision topic chosen by the student. Instructor: Perona. Additional information concerning this course can be found at http://www.vision.caltech.edu/html-files/courses.html.

EE 150. Topics in Electrical Engineering. *Units and terms to be arranged.* Content will vary from year to year, at a level suitable for advanced undergraduate or beginning graduate students. Topics will be chosen according to the interests of students and staff. Visiting faculty may present all or portions of this course from time to time. Instructors: Staff.

EE 151. Electromagnetic Engineering. *12 units (3-2-7); third term. Prerequisites: EE 20 ab or equivalent and ACM 95/100 abc.* Electric fields, magnetic fields, and Maxwell's equations, and their engineering applications. Foundations of circuit theory, plane wave propagation, guided wave propagation, resonators, and antennas. Instructor: Psaltis.

EE 153. Microwave Circuits and Antennas. *12 units (3-2-7); third term. Prerequisite: EE 20 ab.* 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: Pogorzelski.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

EE/Ge 157 abc. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 2 or equivalent.* Introduction to the interaction of electromagnetic waves with natural surfaces and atmospheres. Scattering of microwaves by surfaces and volume scatterers. Microwave and thermal emission from atmospheres and surfaces. Spectral reflection of natural surfaces and atmospheres in the near infrared and visible regions of the spectrum. Review of modern spaceborne sensors and associated technology and data analysis. Emphasis on sensor design, new techniques, ongoing developments, and data interpretation. Examples of applications in geology, planetology, oceanography, astronomy, and atmospheric research. Instructor: Elachi.

EE/Ge 158. Application of Remote Sensing in the Field. *6 units (0-5-1); third term. Prerequisite: EE/Ge 157 ab.* Application of remote-sensing techniques learned in EE/Ge 157 ab to field situations. During spring break students will visit areas in eastern California and western Nevada that have been used as test areas for visible and near-infrared, thermal-infrared, and microwave scattering methods. Satellite, aircraft, and ground spectrometer data will be compared with surface observation by the student. Instructor: Albee.

EE 160. Communication-System Fundamentals. *9 units (3-0-6); third term. Prerequisite: EE 32 ab.* 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: Staff

EE 161. Wireless Communications. *9 units (3-0-6); second 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. Instructor: Staff.

EE 162. Random Processes for Communication and Signal Processing. *9 units (3-0-6); first term. Prerequisite: Some familiarity with probability.* Introduction to single-parameter random processes: stationarity; correlation functions; power spectral density; Gaussian processes. Response of linear systems to random processes. Instructor: Divsalar.

EE 163 ab. Communication Theory. *9 units (3-0-6); second, third terms. Prerequisite: EE 32 ab; EE 162 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. Instructor: Divsalar.

EE 164. Adaptive Filters and Optimal Filters. *9 units (3-0-6); third term. Prerequisites: EE 112 abc and EE 162 or equivalents.* Adaptive FIR and IIR filters, adaptation algorithms, convergence analysis, adaptive FIR lattice filters and other orthogonalizing techniques, recursive least squares techniques, fast-Kalman techniques, stable IIR adaptive filtering, adaptive filtering in subbands, Wiener and matched digital filters, linear predictive coding, normal equations, Levinson's recursion, and associated lattice structures. Some applications from the following areas will be used as motivators: speech compression, spectral factorization, channel equalization, echo and noise cancellation, interference minimization, and antenna arrays. Instructors: Staff.

EE 165. Introduction to Spacecraft Telecommunications Engineering. *9 units (3-0-6); second term. Prerequisites: EE 160 or equivalent, or EE 163 ab.* This course will cover topics in both earth-orbiting satellite and deep-space communications with respect to both ends of the communications link (i.e., the spacecraft and the ground station). Not offered 2000–2001.

EE 167. Data Compression. *9 units (3-0-6); second term. Prerequisite: EE 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. Sub-band coding. Practical algorithms for image and video compression. Instructor: Dolinar.

EE/APh 180. Solid-State Devices. *9 units (3-0-6); second term. Prerequisite: EE 20 ab.* 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. Instructor: Scherer.

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

APh/EE 183 abc. Fundamentals of Electronic Devices. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 184 abc. Computer Architechture. *9 units (3-3-3).* For course description, see Computer Science.

EE 185 ab. Microfabrication Technology for Solid-State Devices. *9 units (3-0-6); second, third terms. Prerequisites: APh 9, EE/APh 180, or instructor's permission.* Course in advanced (silicon) microfabrication technology. Topics: lithography; oxidation; diffusion; ion implantation; thin-film deposition; wet and dry etching; metalization. The use of these techniques to fabricate a wide variety of solid-state devices, including MOSFETs, microsensors, and microactuators will be discussed. Practical equipment for these processes will also be included. Instructor: Tai.

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/CS/EE 188 ab. Computation Theory and Neural Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

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.

CNS/EE 248. Sensory Information Processing Laboratory. *12 units (1-2-9).* For course description, see Computation and Neural Systems.

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.

ENGINEERING (GENERAL)

E 2. Engineering and Entrepreneurship. *2 units (1-0-1); first term.* Reflections on engineering and entrepreneurship by co-founder of TRW, Dr. Simon Ramo. Items to be covered include: the nature of practical engineering; entrepreneurship; financing a company; manufacturing; the role of government; the international economy; environment, safety, and liability; and large versus small companies. Discussion will center around a number of current issues, such as electric vehicles, supersonic transports, the information superhighway, interactive television, genetic engineering, and others. Graded pass/fail. Instructor: Ramo. Not offered 2000–2001.

E 5. Laboratory Research Methods in Engineering and Applied Science. *6 units (1-3-2); second term. 6 units credit allowed toward freshman laboratory requirement.* An introduction to experimental methods and problems typical of a variety of engineering fields. Staff members representing various areas of interest within engineering and applied science will supervise experiments related to their specialty. As the situation permits, students are given some choice in selecting experiments. Instructors: Staff. Not offered 2000–2001.

E 10. Technical Seminar Presentations. *3 units (1-0-2); second, third terms. (Only graduating students required to take E 10 are permitted to preregister. Others wishing to take the course should come to the organizational meeting and will be admitted if there is room. NOTE: Those who neither preregister nor attend the O.M. 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 blackboards, overhead projectors, and slide projectors. Instructors: Staff.

E 102. Entrepreneurial Development. *6 units (3-0-3); 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; merger and acquisitions; and closing down operations. Lectures include presentations by invited experts in various specialties and keynote guest lecturers of national stature in technology business development. Graded pass/fail. Instructor: Baldeschwieler.

E 103. Management of Technology. *9 units (3-3-3); 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. The course is designed for

students considering working in companies (any size including start-up) or perhaps eventually going to business school. Topics include technology as a growth agent, financial fundamentals, integration into other business processes, product life cycle, product development pipeline, learning curves, risk assessment, financial implications, technology trend methodologies (scenarios, projections), portfolio management and decision criteria, motivation, rewards and recognition, and sourcing and joint venturing. E 102 (Entrepreneurial Development) and E 105 (Product Design) are useful but not required precursors. Instructor: Pickar.

E 105. Product Design. *9 units (3-3-3); first term.* Course to provide the student with a working knowledge of contemporary methods of product design to meet the constraints of cost, performance, quality, and time to market. Areas covered include design for X (X=manufacturability/assembly, six sigma quality, environment, failure modes and effects analysis, test, etc.). The integration of customer needs and financial return will be discussed with specific examples. Other areas covered include Baldrige criteria, quality functional development, program management, and rapid prototyping. Some outside speakers and local field trips will be included. Instructor: Pickar.

E 106. Internet Business. *9 units (3-3-3); first term. Prerequisites: E 102, E 103, and E 105 are recommended.* This course will offer the basic principles of Internet business. The subjects will include Internet Technology issues, but will stress new business models. Innovations in customer linkages (e-commerce) as well as business-to-business models will be covered. Some topics included will be first-mover advantage, value chains and the value proposition, infomediaries, on-line marketplaces, customer relationship management, pure and hybrid business models, business networks, response strategy of traditional business, management issues, etc. The course material will be presented in both lecture form as well as through class discussion of assigned Harvard Business School (and original) case studies. An integral part of the class will be team projects; teams will be required to build Web-based prototypes demonstrating business model innovation. Instructor: Pickar.

E 150 abc. Engineering Seminar. *1 unit (1-0-0); 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. Instructors: Staff.

ENGINEERING GRAPHICS *(see Mechanical Engineering)*

ES 200 abc. Topics in Bioengineering. *9 units (3-0-6); first, second, third terms.* First two terms: the foundation of low-Reynolds-number fluid physics, the motion of a rigid or flexible body, flows of suspensions, and transfer processes. Third term: various applications to rheology, blood flow in living systems, chemical flow problems, motility of micro-organisms, and bioconvection. Instructors: Staff.

ES/CE 204 abc. Hydrodynamics of Free Surface Flows. *9 units (3-0-6); first, second, third terms. Prerequisites: CE/ME 101 abc, and AM 125 abc or equivalent.* Theory of surface waves in a dispersive medium. Infinitesimal waves and wave resistance of floating or submerged bodies. Ship hydrodynamics. Theory of the planing surface and hydrofoil. Scattering and diffraction of surface waves. Geometrical wave approximation. Hydrodynamic stability. Nonlinear waves and existence theorems. Shallow-water waves. Open-channel flows and river waves. Flows with shear and stratification of density and entropy. Free streamline theory for jets, wakes, and cavities. General theory for curved obstacles; existence and uniqueness. Unsteady flows with jets and cavities. The course material in the third term may vary, depending upon the needs and interests of the class. Not offered every year. Instructor: Staff.

ES 250 abc. Research in Engineering Science. *Hours and units by arrangement.* By arrangement with members of the staff, properly qualified graduate students are directed in research in Engineering Science.

ENGLISH

En 1 ab. English as a Second Language. *9 units (3-0-6 or 4-0-5); first, second terms.* A program in the fundamentals of English composition for non-native speakers of English, required for foreign students in need of supplementary instruction before entering freshman humanities courses. Students will be assigned to either En 1 b or the two-quarter sequence of En 1 ab on the basis of a diagnostic examination. *Not available for credit toward the humanities–social science requirement.* Instructors: Fonseca, Linden-Martin.

En 2. Basic English Composition. *9 units (2-2-5); first term.* A course in the fundamentals of English composition for native speakers of English, required for students in need of supplementary instruction before entering freshman humanities courses. Students will be assigned to En 2 on the basis of a diagnostic examination. *Not available for credit toward the humanities–social science requirement.* Instructor: Fonseca.

ENGLISH AS A SECOND LANGUAGE (ESL)

Please see pages 214 and 215 for requirements regarding English competency. All of the following courses are open to international graduate students only. None are available for credit.

ESL 101 ab. Oral Communication and Pronunciation. *Noncredit; 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 quarter is required for all first-year international students designated by the ESL screening process. Instructors: Linden-Martin and 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: Linden-Martin and Laib.

ESL 103. English in Everyday Life. *Noncredit; first, second, and 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: Linden-Martin and Laib.

ESL 104. Pronunciation Improvement and Accent Reduction. *Noncredit; second term only.* 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: Linden-Martin and Laib.

ESL 105. Oral Presentation and Public Speaking. *Noncredit; second and 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: Linden-Martin and Laib.

ESL 106. Writing Seminar. *Noncredit; third term only.* 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: Linden-Martin and Laib.

Env 1. Engineering Problems of the Environment. *9 units (3-0-6); third term. Prerequisites: Ph 1 ab, Ch 1 ab, and Ma 1 ab.* An introduction to the engineering design of measures to limit impacts on the environment. Global and local cycles in the hydrosphere, atmosphere, and biosphere; energy and materials balance in environmental problems; source control of pollutants. The process of establishing environmental goals is discussed. Instructor: Staff. Not offered 2000–2001.

Env 90. Undergraduate Laboratory Research in Environmental Engineering Science. *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. Seniors may prepare a thesis with approval of the EES faculty at the beginning of the senior year; in this case, registration should be for at least three consecutive terms. Graded pass/fail. Instructors: Staff.

Env 100. Special Topics in Environmental Engineering Science. *6 or more units as arranged. Prerequisite: instructor's permission.* Special courses of reading, problems, or research for graduate students working for the M.S. degree, or qualified undergraduates. Graded pass/fail. Instructors: Staff.

Env 112 abc. Hydrologic Transport Processes. *9 units (3-0-6); first, second, third terms. Prerequisites: ACM 95/100 abc; ME 19 ab; and some knowledge of elements of hydrology (may be satisfied by special reading assignments).* The hydrologic cycle and analysis of hydrologic data; dynamic similitude; turbulent shear flow in rivers; and hydraulic models. Transport and dispersion of solutes, sediments, and heat; turbulent plumes and buoyant jets; surface heat transfer, evaporation, and density stratification in natural waters. Engineering of outfalls. Flow and pollutant transport through porous media; groundwater problems. Not offered 2000–2001.

Env 116. Aerosol Measurements. *9 units (3-2-4); third term. Prerequisites: ChE/Env 158 or permission of instructor.* Lectures and experiments on the sampling and measurement of aerosol size distributions, instrument calibration, particle characterization, and particle sampling. Given in alternate years; offered 2000–2001. Instructor: Flagan.

Env/ChE 142 ab. Chemistry of Natural Water Systems. *9 units (3-0-6); first, second terms. Prerequisite: Ch 1.* Principles of inorganic and physical chemistry applied to quantitative description of processes in natural waters: Thermodynamic and kinetic aspects of electrolyte solutions, carbon dioxide/carbonate systems, dissolution and precipitation,

metal-ligand complexes, electron transfer, surface chemistry of aquatic particles, and particle aggregation and stabilization processes in water. Instructor: Hering.

Env 143. Water Chemistry Laboratory. *9 units (0-6-3); third term. Prerequisite: Env/ChE 142 ab.* Laboratory experiments dealing with the major and minor constituents of natural waters. Topics include seawater chemistry, heterogeneous equilibria, redox processes, adsorption, and particle coagulation. Instructor: Hering. Not offered 2000–2001.

Env 144. Ecology. *6 units (2-1-3); first term.* Basic principles of ecology and ways in which human activities can influence natural populations. Not offered 2000–2001.

Env 146. Chemical Reaction Engineering for Water Quality Control. *9 units (3-0-6); third term. Prerequisite: Env/ChE 142 ab.* Basic principles of reaction engineering applied specifically to unit operations used in water and wastewater engineering. Emphasis on underlying chemical principles. Topics: adsorption, catalysis, chlorination, coagulation and flocculation, gas transfer, ion exchange, nitrogen and phosphorus removal, oxidation-reduction, ozonation, precipitation, reverse osmosis, and ultrafiltration. Instructor: Hoffmann.

Env/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. Weather and Climate. *(3-0-6); first term.* Atmospheric radiation, greenhouse effect, ice ages, ozone hole, atmospheric and oceanic circulation and chemistry, numerical modeling of weather and climate. Instructor: Ingersoll.

b. Global Biogeochemical Cycles. *(3-0-6); second term.* Global biogeochemical cycles, fluxes, and chemical reservoirs in the solid earth, atmosphere, and oceans. Regulation of atmospheric composition by photosynthesis and microbial processes. Variability in biogeochemical cycles during the Pleistocene, and recent modification by human activity. Constraints on fluxes from remote sensing data, isotope sampling, and models. Instructor: Randerson.

c. Terrestrial Surface System. *(3-2-4); third term.* Natural surficial processes, soils, vegetation, fresh water, and their modification by human interactions. Present in context of Holocene and Pleistocene. Remote sensing applications. Instructor: Staff. Not offered 2000–2001. Additional information concerning this course can be found at http://www.gps.caltech.edu/~ge148/2000/.

Ge/Env 149. Marine Geochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Env 150 abc. Seminar in Environmental Engineering Science. *1 unit (1-0-0); 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: Hering.

Env/Ge 152 abc. Physics of Atmospheres and Oceans. *9 units (3-0-6); first, second, third terms. Recommended: Env/Ge 148, ME 18, ME 19, ACM 95/100, or equivalent.* Fundamental physical processes in atmospheres and oceans. Thermodynamics, condensation, precipitation, hydrostatic balance, stability, convection, radiation, remote sensing, clouds, climate, primitive equations, geostrophic balance, turbulence, waves, hydrodynamic instability, the general circulation, numerical modeling. Applications include El Niño, climate of the past 100 years, the last ice age, clouds and Earth's radiation budget, convection and the planetary boundary layer, Earth's middle atmosphere, planetary atmospheres. Instructors: Ingersoll (c), Yung (a, b).

Ge/Env 154. Readings in Paleoclimate. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

Ge/Env 155. Paleoceanography. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ChE/Env 157. Sources and Control of Air Pollution. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Env 158. Aerosol Physics and Chemistry. *9 units (3-3-3).* For course description, see Chemical Engineering.

ChE/Env 159. Atmospheric Chemistry and Physics of Air Pollution. *9 units (3-0-6).* For course description, see Chemical Engineering.

Env/Bi 166. Microbial Physiology. *9 units (3-0-6); second term; alternate years. Recommended prerequisite: one year of general biology.* A lecture and discussion 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. Not offered 2000–2001.

Env/Bi 168. Microbial Diversity. *9 units (3-0-6); third term. Recommended prerequisite: one year of general biology.* A lecture and discussion course on the metabolic diversity of prokaryotic microorganisms. Each of the major metabolic groups of prokaryotes will be discussed in terms of their biochemistry, genetics, and ecology. The course will comprise a comprehensive survey of the known microbial groups, their capabilities, and their importance in geochemical cycling and industrial applications. Instructor: Nealson.

Env/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6); third term. Prerequisites: Ch 21 ab, Env/Ge 152 ab or consent of the instructors.* A detailed course about chemical transformation in the 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: Wennberg, Seinfeld.

Env/Ge/Ch 172. Atmospheric Chemistry II. *9 units (3-0-6); first term. Prerequisites: Env/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; formation of aerosol in remote environments; coupling of dynamics and photochemistry; development and use of modern remote sensing and in situ instrumentation. Instructors: Wennberg, Seinfeld.

Env/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6); first and second terms.* A detailed analysis of the important chemical reactions and physico-chemical 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.

Env 200. Advanced Topics in Environmental Engineering Science. *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.

Env 208. Special Topics in Microbiology. *6 units (2-0-4); second term; alternate years. Prerequisite: Env/Bi 168 and instructor's permission.* A lecture and discussion course to cover topics of current interest in the field of microbiology. As the topics will vary from year to year, it may be taken any number of times. Potential topics: bioremediation, genetics in unusual microorganisms; risk assessment and the release of genetically engineered organisms to the environment; environmental molecular biology. Not offered 2000–2001.

Env 210. Advanced Seminar in Microbiology. *3 units (1-0-2); first term. Prerequisite: instructor's permission.* A seminar course for advanced graduate students and staff to discuss current research and technical literature in the field of microbiology. As the topics will vary, it may be taken any number of times. Not offered 2000–2001.

Env 214 abc. Advanced Environmental Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: CE/ME 101 or Ae/APh 101, ACM 101 or AM 125.* A study of the transport and dispersing properties of fluid motions in the air, oceans, estuaries, rivers, lakes, and groundwater. Emphasis is given to the processes and scales of motion that are important to engineering problems of pollution control. Instructor: Staff. Not offered 2000–2001.

Env 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. Instructors: Staff.

Env 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 Scripps Institution of Oceanography under an exchange program. Graduate students majoring in environmental engineering science, who may take a subject minor in oceanography for the Ph.D. degree, should consult the executive officer for more information.

FRENCH *(see Languages)*

GEOLOGICAL AND PLANETARY SCIENCES

Geology, Geobiology, Geochemistry, Geophysics, Planetary Science

Ge 1. Earth and Environment. *9 units (3-3-3); third term.* An introduction to the ideas and approaches of earth and environmental sciences, including both the special challenges and viewpoints of this kind of science as well as the ways in which basic physics, chemistry, and biology relate to these sciences. In addition to a wide-ranging lecture-oriented component, there will be a required field trip component (two weekend days), and a special research topic (often lab-oriented) chosen from many alternatives and to be carried out in small groups each led by a professor. 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. Instructors: Farley, staff. *Satisfies the menu requirement of the Caltech core curriculum.*

Ge 10. Frontiers in Geological and Planetary Sciences. *3 units (2-0-1); third term. Open for credit to sophomores, juniors, and seniors; the course may be taken multiple times. Prerequisites: Ge 1 (enrollment can be concurrent), or consent of instructor.* 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. A second hour is used to discuss proposals written by class members for future research projects in the area of each seminar topic. 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: Stolper, staff.

Ge 11 abc. Introduction to Earth and Planetary Sciences. *9 units each term. Prerequisites: Ch 1, Ma 1, and Ph 1; or consent of instructor.* Comprehensive, integrated overview of the 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. Weathering, erosion, and sedimentary rocks. Metamorphism and metamorphic rocks. Rock deformation and mountain building. Role of aqueous, atmospheric, glacial, and tectonic processes in shaping the earth's surface and our environment. Earth resources. Field trips, interpretation of geological maps, and laboratory study of earth materials (minerals and rocks). Instructor: Eiler.

b. Earth and the Biosphere. *(3-3-3); second term.* Systematic analysis of the origin and evolution of life in the solar system, and its impact on the atmosphere, hydrosphere, and climate of Earth. Archean surface environments and production of oxygen. Bacterial evolution, photosynthesis, genes as fossils. Banded iron stones (BIFs), algal mats, stromatolites, global glaciation, and molecular evolution. Biological fractionation of stable isotopes. Numerical calibration of the geological time scale, the Cambrian evolutionary explosion, mass extinction events, and human evolution. The course usually includes one major field trip to Baja, and several laboratory studies of fossils, Precambrian rocks, and geological processes. Instructor: Kirschvink.

c. Planetary Sciences. *(3-0-6); third term.* A broad introduction to what is known about the origin, evolution, and present state of the solar system. Observations on young solar mass stars, disks, and extrasolar planets, as well as meteorite properties and planet formation models, are the constraints on solar-system origin. Based on data from earth-based observations, planetary spacecraft, and extraterrestrial materials, the evolution and present states of planetary objects are addressed systematically by considering small bodies (comets and asteroids), the terrestrial planets, the giant planets, and finally, the icy bodies of the outer solar system. Instructor: Burnett. Not offered 2000–2001.

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 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 division undergraduate research counselors, Professors Rossman and Kirschvink. Graded pass/fail.

Ge 66. Planet Earth. *9 units (3-0-6); second term. Prerequisites: Ma 2, Ph 2.* An introduction to the geophysics of the solid earth. Formation of planets. Structure and composition of the earth. Interactions between crust, mantle, and core. Surface and internal dynamics. Mantle convection. Imaging of the interior. Seismic tomography. Instructor: Anderson.

Ge 100 abc. Geology Club. *1 unit (1-0-0); 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. Prerequisites: Ch 1, Ma 2, Ph 2, or the equivalents, or consent of instructor.* Historical deduction in geological and planetary sciences. Nucleosynthesis and chemical differentiation of the solar system; distribution of the elements in the earth; isotopic systems as tracers and clocks; igneous, surficial, metamorphic, and structural processes; tectonics of the lithosphere; evolution of the biosphere; global geochemical and biogeochemical cycles. Instructors: Asimow and Adkins.

Ge 102. Introduction to Geophysics. *9 units (3-0-6); second term. Prerequisites: Ma 2, Ph 2, or Ge 108, or the 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: Gurnis.

Ge/Ay 103. Introduction to the Solar System. *9 units (3-0-6); third term. Prerequisites: Ph 2, Ma 2, or Ge 108, or the equivalents.* Formation and evolution of the solar system. Interiors, surfaces, atmospheres of the sun, planets, and satellites. Orbital dynamics, chaos, and tidal friction. Cratering. Comets and asteroids. Magnetic fields, dynamos, solar wind, heliosphere, magnetospheres. Extrasolar planetary systems. Instructor: Goldreich. Not offered 2000–2001.

Ge 106. Introduction to Field and Structural Geology. *12 units (3-6-3); second term. Prerequisite: Ge 11 ab.* Introduction to continuum mechanics and rock deformation. Interpretation of the record of deformation of the earth's crust on megascopic, mesoscopic, and microscopic scales. Tectonics of mountain belts. Laboratories introduce geometrical and graphical techniques of structural analysis using geologic maps. Field trips introduce methods of geologic mapping in preparation for Ge 120. Instructor: Wernicke.

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. Instructor: Wasserburg.

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 held in the third term, which will discuss the scientific background for the chosen field area, along with the theoretical basis and implementation of the various measurement techniques. The 6–10 day field/data analysis component is covered in Ge 111 b. May be repeated for credit with an instructor's permission. Instructors: Simons, Clayton, Stock.

a. Applied Geophysics Seminar. *6 units (3-3-0); third term. Prerequisite: Consent of instructor(s).*

b. Applied Geophysics Field Course. *9 units (0-3-6); summer term. Prerequisite: Ge 111 a.*

Ge 112. Geomorphology and Stratigraphy. *12 units (3-5-4); first term. Prerequisite: Ge 11 ab.* This course is an introduction to Earth's landscapes and strata. We explore the nature of fluvial, lacustrine, glacial, volcanic, tectonic, and various marine landforms and sediments. Their character and sequencing are the strata that enable us to understand geologic history and processes. The course will describe modern, active systems and the interpretation of paleoenvironments and paleoclimates of the past million years. The nature and genesis of sequence architecture of sedimentary basins will also be introduced. Field trips and laboratory exercises. Instructor: Sieh.

Ge 114. Mineralogy. *12 units (3-6-3) or 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 characterization and identification of important minerals by physical and optical properties. The 12-unit course is required for geology and geochemistry majors, and includes additional laboratory studies on optical crystallography and use of the petrographic microscope. Instructor: Rossman.

Ge 115 ab. Petrology and Petrography. Systematic study of rocks and rock-forming minerals with emphasis on use of the petrographic microscope and megascopic identification; interpretation of mineral assemblages, textures, and structures; problems of genesis.

a. Igneous Petrology and Petrography. *12 units (3-6-3) or 6 units (3-0-3) with consent of instructor; second term. Prerequisite: Ge 114.* The mineralogical and chemical composition, origin, occurrence, and classification of igneous rocks, considered mainly in the light of chemical equilibrium and of experimental studies. Detailed consideration of the structures, phase relations, and identification of the major igneous minerals. Instructor: Stolper.

b. Metamorphic Petrology and Petrography. *12 units (3-6-3) or 6 units (3-0-3) with consent of instructor; 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. Detailed consideration of structure, phase relations, composition, and determination of the major metamorphic minerals. Instructor: Eiler.

Ge 120. Summer Field Geology. *12 units (0-12-0); summer. Prerequisites: Ge 11 ab, Ge 106; or consent of instructor.* Intensive course in techniques of field observation. Course includes two and one-half weeks of mapping in a well-exposed area of the southwestern United States and the preparation of a report, in September prior to registration week. Instructor: Saleeby.

Ge 121 ab. Advanced Field and Structural Geology. *12 units (0-9-3); second, third terms. Prerequisites: Ge 11 ab and 106, or consent of instructor.* Field mapping and supporting laboratory studies in topical problems related to southern California tectonics and petrogenesis. Each year the sequence offers a breadth of experience in igneous, metamorphic, and sedimentary rocks. Instructors: Stock (second); Wernicke (third term).

Ge 122. Geologic Hazard Assessment. *12 units (1-8-3); summer term. Prerequisites: Ge 120 or equivalent, or consent of instructor.* Two and one-half weeks of intensive field-based description and evaluation of the deposits and landforms related to a geologic hazard. Field location will vary from year to year, but will focus on a particular locale, either within the U.S. or abroad, where a seismic, volcanic, slope-stability, or other hazard can be documented and evaluated. Instructor: Sieh.

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 time scale. Given in alternate years; offered 2000–2001. Instructor: Kirschvink.

a. *9 units (3-3-3); second 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.

b. *6 units (0-0-6); third term. Prerequisite: Ge 124 a.* A field trip to the southwest U.S. to study the physical stratigraphy and magnetic zonation, followed by lab analysis.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6); second term. Prerequisite: consent of instructor.* 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 2000–2001.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); third term. Prerequisite: consent of instructor.* The chemistry of the interstellar medium, of protostellar nebulae, and of primitive solar-system objects with a view towards 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, time scales for physical and chemical change, chemical processes leading to change, observational constraints, and various models that attempt to describe the chemical state and history of cosmological objects in general and the early solar system in particular. Instructor: Blake. Given in alternate years; offered 2000–2001.

Ge 131. Planetary Structure and Evolution. *9 units (3-0-6); first 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. Given in alternate years; not offered 2000–2001.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6). 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 2000–2001.

Ge/Ay 133. The Formation, Evolution, and Detection of Planetary Systems. *9 units (3-0-6).* Review current theoretical ideas and observations pertaining to the formation and evolution of low-mass stars and their associated planetary systems. Ongoing and proposed observational strategies for the detection of extra-solar planets, planetary systems, and brown dwarfs will be discussed and analyzed. Instruction will be via seminars by staff and students. Instructors: Brown, Kulkarni. Given in alternate years; not offered 2000–2001.

Ge 135. Regional Geology of Southern California (Seminar). *6 units (3-0-3); second term. Prerequisite: Ge 11 ab or equivalent.* Reading and discussion of selected topics in the geology of southern California and adjacent areas, with emphasis on outlining the important regional research problems. Instructor: Silver.

Ge 136. Regional Field Geology of the Southwestern United States. *9 units (1-0-8); third term. Prerequisites: Ge 11 ab or instructor's permission.* Includes at least nine days of weekend field trips into areas of the southwestern United States 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: Sharp. Not offered 2000–2001.

Ge 140 ab. Introduction to Isotope Geochemistry. *9 units (2-0-7); second, third terms. 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 stable and radiogenic isotope geochemistry will be illustrated by examples of geologic or planetary processes.

a. *second term.* The processes responsible for natural variations in the isotopic composition of the lighter elements (H, C, O, N, Si, S), with applications to geochemical problems. Isotopic fractionation mechanisms. Use of oxygen and hydrogen isotopic data to study the origin and history of various types of rocks and to determine the climatic records in cherts, carbonate fossils, ancient woods, and ice cores. Significance of $^{34}S/^{32}S$ and $^{13}C/^{12}C$ variations in the sulfur and carbon cycles, with applications to problems in geobiology. Use of stable isotopes in the study of meteorites and lunar materials. Instructor: Taylor.

b. *third term.* The origin and evolution of radiogenic parent-daughter systems in nature, with application to the determination of the ages of rocks and minerals, and of the earth, meteorites, and the moon, mainly utilizing the U-Th-Pb-He, Rb-Sr, Sm-Nd, K-Ar, and ^{14}C systems. Applications to problems of igneous petrology and metamorphism, and to the large-scale differentiation of the planets. Instructor: Wasserburg.

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. Instructor: Saleeby.

Env/Ge 148 abc. Global Environmental Science. *9 units; (3-0-6) first and second terms; (3-2-4) third term.* For course description, see Environmental Engineering Science.

Ge/Env 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 exhange, nutrient uptake by the biota, radioactive tracers, redox processes in the water column and sediments, carbonate chemistry, and ventilation. Alternates with Ge 155. Instructor: Adkins.

Ge 151 a. Fundamentals of Planetary Surfaces. *9 units (3-0-6); second term. Prerequisite: Ge 11 abc or equivalent.* 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. Grades assigned on basis of homework and written and oral term project. Instructors: Murray and staff. For more information, see http://www.gps.caltech.edu/~ge151/.

Ge 151 b. Topics in Planetary Surfaces. *6 units (3-0-3); third term. Prerequisite: Ge 151 a or permission of the instructor.* 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. Grades based on assigned oral and written presentations. May be repeated for credit. Instructors: Albee and staff.

Env/Ge 152 abc. Physics of Atmospheres and Oceans. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Ge 153. Planetary Radio Astronomy. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Investigates the atmospheres and surfaces of the planets and their satellites using microwave techniques. Information from the literature and current observations in millimeter and submillimeter spectroscopy, thermal microwave emission, radio and visual occultations, and radar astronomy will be discussed from the standpoint of the physics and chemistry of solar-system objects. Instructor: Staff. Given in alternate years; not offered 2000–2001.

Ge/Env 154. Readings in Paleoclimate. *6 units (2-0-4); second term. Prerequisite: consent of instructor.* Lectures and readings in areas of current interest in paleoceanography and paleoclimate. Instructor: Adkins. Alternates with Ge 155; offered 2000–2001.

Ge/Env 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- to a few hundred-thousand years, with some consideration of longer time scales. 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. Alternates with Ge 149. Not offered 2000–2001.

EE/Ge 157 abc. Introduction to the Physics of Remote Sensing. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ge 158. Application of Remote Sensing in the Field. *6 units (0-5-1).* For course description, see Electrical Engineering.

Ge 160 abc. Seismological Laboratory Seminar. *1 unit (1-0-0); first, second, third terms.* Presentation of current research in geophysics by students, staff, and visitors. Graded pass/fail. Instructor: Helmberger.

Ge 161. Seismology. *9 units (3-0-6); second term. Prerequisites: Ge 176 or ACM 95/100, or consent of instructor.* Covers essential material in modern broadband seismology; elastic wave propagation, and methods for computing synthetic seismograms; applications to the determination of earth structure and source estimation at various wavelengths; special applications to modeling the broadband data from TERRAscope. Instructor: Helmberger.

Ge 162. Long-Period Seismology. *9 units (3-0-6); third term.* Free oscillations and surface waves. Equations of motion that govern the vibrations of a pre-stressed, rotating, self-gravitating Earth model. Normal modes of a spherically symmetric Earth model: toroidal and spheroidal modes, Love and Rayleigh surface waves, and mode-ray duality. Effects of rotation, hydrostatic ellipticity, and lateral heterogeneity on free oscillations. Description of an earthquake in terms of the centroid-moment tensor. Free oscillations of an anelastic Earth model: attenuation, physical dispersion, and the Kramers-Kronig relations. Instructor: Tromp.

Ge 164. Fluid Mechanics in the Earth Sciences. *9 units (3-0-6); second term.* A unified presentation of the principles of fluid mechanics. Topics chosen from: control volume analysis, conservation equations. Bernoulli equation. Viscous flow: Stokes flow, boundary-layers, jets, chaotic mixing. Rotating fluids: geostrophic motion. Buoyancy-driven flows: buoyant plumes, stratified flow. Turbulence: turbulent structure, turbulent mixing. Two-phase flow: particle-laden flows, erosion, sedimentation, bubbly flows, foams. Flow in porous media. Compressible flow: supersonic flow, shock waves, shock Hugoniot, refraction. Instructor: Sturtevant. Not offered 2000–2001.

Ge 165. Digital Signal Analysis. *9 units (3-0-6); first term. Prerequisites: Fourier transforms or permission of instructor.* Discrete data analysis with particular emphasis on geophysical problems. Topics: Z-transforms, discrete Fourier transforms, filtering, deconvolution, autoregressive-moving average models, spectral analysis, missing data, model fitting, and two-dimensional and multichannel analysis. Instructor: Clayton.

Ge 166. Physics of the Earth's Interior. *9 units (3-0-6); second term.* Interpretation of observed geophysical data describing the earth's interior in terms of the earth's evolution, ongoing geodynamic processes, and the composition and thermal state of the mantle and core. Instructor: Anderson.

Ge 167. 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. Instructor: Goldreich. Not offered 2000–2001.

Ge 168. Crustal Geophysics. *9 units (3-0-6); third term. Prerequisite: ACM 95/100 or equivalent, or permission of instructor.* The analysis of geophysical data related to crust processes. Topics include reflection and refraction seismology, tomography, gravity, magnetics, and geodesy. Instructor: Clayton.

Ge 169. Inverse Methods for Earth Scientists. *9 units (3-0-6); second term. Prerequisite: Basic linear algebra.* Introduction to parameter estimation techniques for both over- and underdetermined problems. Covered topics include linear and nonlinear inverse methods, and the use of constraints. Covered methods will include the bootstrap, Monte Carlo techniques, genetic algorithms, and Kalman filters. Emphasis will be placed on how the choice of parameterization affects the results. Examples will be taken from the earth sciences. Homework will make extensive use of Matlab. Instructor: Simons.

Env/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Env/Ge/Ch 172. Atmospheric Chemistry II. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Env/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Ge 176. Elementary Seismology. *9 units (3-0-6); first term.* This course covers seismology at an elementary level. Starting from phenomenological discussion of earthquake processes, this course will cover the basic principles of classical seismology, relation between

earthquakes and plate motion, simple physics involving some rock mechanics concepts, and the effects of earthquakes. Many examples will be shown, with some exercises. Instructor: Kanamori.

Ge 177. Geology of Earthquakes. *12 units (3-3-6); second term. Prerequisites: Ge 106 or equivalent.* Geologic manifestations of recent crustal deformation. Geomorphology, stratigraphy, and structural geology 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, including case studies of selected earthquakes. Instructor: Sieh. Given in alternate years; not offered 2000–2001.

Ge 180. Plate Tectonics. *9 units (3-0-6); first term. Prerequisites: 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. Interpretation of geologic data in the context of plate tectonics; plate tectonic evolution of the ocean basins. Given in alternate years; offered 2000–2001. Instructor: Stock. Additional information concerning this course can be found at http://www.gps.caltech.edu/~jstock/Ge180.html.

CE/Ge 181. Engineering Seismology. *9 units (3-0-6).* For course description, see Civil Engineering.

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. Instructors: Staff.

Ge 203. Special Topics in Atmospheres and Oceans. *9 units (3-0-6); third term. Recommended: Env/Ge 148, ACM 95/100, Ph 106, or equivalent.* Photochemistry of planetary atmospheres, atmospheric evolution, comparative planetology, climate change. Instructor: Ingersoll.

Ge 211. Applied Geophysics II. *Units to be arranged. Prerequisite: Consent of instructor.* 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), 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. Offered spring term, 2000–2001. Instructors: Stock, Clayton, and Staff. For more information, see http://www.gps.caltech.edu/academics/courses/courses.html#ge211.

Ge 212. Thermodynamics of Geological Systems. *9 units (3-0-6); first term. Prerequisite: Ch 21 abc, Ge 115 abc, or equivalents.* Chemical thermodynamics, with emphasis on applications to geologic problems. Heat flow, diffusion, phase transformations, silicate phase equilibria, solid solutions, the effect of H_2O in silicate melts, and equilibrium in a gravitational field. Text: *Chemical Thermodynamics*, Prigogine and Defay. Instructor: Taylor. Given in alternate years; offered 2000–2001.

Ge 214. Spectroscopy of Minerals. *9 units (3-0-6); third term. Prerequisite: Ge 114, Ch 21, or instructor's permission.* The origin of color, pleochroism, and luminescence in minerals, infrared absorption spectroscopy of mineral substances. The application of spectroscopic methods to mineralogical problems, including site populations and other optical properties. Given in alternate years; offered 2000–2001. Instructor: Rossman.

Ge 215 abc. Topics in Advanced Petrology. *12 units each term (3-6-3); first, second, third terms. Prerequisites: Ge 115; Ch 21 recommended.*

a. Chemical Petrology. *First term.* Lectures, seminars, and laboratory studies of the chemical reactions that occur in rocks. Emphasis on rock-water interactions, mineral deposition, hydrothermal alteration, and the formation of ore deposits. Instructor: Taylor. Given in alternate years; not offered 2000–2001.

b. Advanced Igneous Petrology. *Third term.* Lectures, seminars, and laboratory studies on igneous petrogenesis and rocks, emphasizing experimental studies. Instructor: Asimow. Given in alternate years; not offered 2000–2001.

c. Advanced Metamorphic Petrology. *Third term.* Lectures, seminars, and laboratory studies on metamorphic petrogenesis and rocks. Emphasis on the interpretation of natural assemblages and of mineral relations. Instructor: Staff. Given in alternate years; not offered 2000–2001.

Ge 225 abc. Planetary Sciences Seminar. *1 unit (1-0-0); 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. Instructors: Staff.

Ge/Ay 226. Observational Planetary Astronomy. *9 units (3-3-3); second term. Prerequisite: Ay 122 or consent of instructor.* Discussion of applications of astronomical techniques to the study of solar system bodies. Topics will include the study of atmospheres, surfaces, and magnetospheres using ground- and space-based telescopes at wavelengths ranging from radio to X-ray wavelengths. Laboratory work will emphasize the acquisition, reduction, and interpretation of planetary astronomical data. Instructor: Brown. Given in alternate years; not offered 2000–2001.

Ge 229. Glaciology. *9 units (3-0-6); third term.* Characteristics of existing glaciers and ice sheets; ice-age glaciers; glacier flow and fracture mechanics in relation to ice physics; mass and energy balance and response to climatic change; glacial erosion and deposition; causes of glaciation. Instructor: Kamb. Given in alternate years; not offered 2000–2001.

Ge 232. Chemistry of the Solar System. *9 units (3-0-6); second term. Prerequisite: Ge 140 b or consent of instructor.* 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 2000–2001.

Ge 236. Applications of Rare Gases to Earth Science Problems. *9 units (3-0-6); offered by announcement only; third term. Prerequisite: instructor's approval.* Discussion of the principles, applications, and limitations of rare gases as records of terrestrial processes. Origin and behavior of rare gases in natural systems. Specific areas to be considered include: K/Ar and $^{40}Ar/^{39}Ar$ dating; Ar thermochronology; surface-exposure dating; rare gas constraints on mantle evolution and

models of atmosphere formation; additional applications in geology, hydrology, paleoclimatology, and oceanography. Instructor: Farley.

Ge 240. Advanced Isotope Geochemistry. *9 units (3-0-6); offered by announcement only. Prerequisite: Ge 140 ab or permission of instructor.* Lectures and problems on the variations in the isotopic composition of elements in nature, with applications to studies of the origin of the solar system, planetary evolution, igneous and metamorphic petrology, hydrothermal alteration and ore deposits, and the origin and history of the earth's atmosphere and hydrosphere. Emphasis is placed on the integration of stable and radiogenic isotope studies in current research areas, utilizing problem sets and extensive reading of articles in scientific journals, including discussion of instrumentation and modern techniques of measurement of isotopic and chemical abundances. Instructor: Wasserburg.

Ge/Bi 244 ab. Paleobiology Seminar. *5 units; second, third terms.* Critical reviews and discussion of classic investigations and current research in paleoecology, evolution, and biogeochemistry. Instructor: Kirschvink.

Ge/Bi 246. Geomicrobiology Seminar. *6 units (2-0-4); second term. Recommended prerequisite: Env/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: Newman.

Ge 248. Geodynamics. *9 units (3-0-6); third term.* Application of continuum mechanics to geologic problems of mass and heat transfer; emphasis on problems of plate tectonics. Basic concepts include stress, infinitesimal and finite strain, brittle failure, elastic, plastic, viscous, power law, and visco-elastic deformation. These concepts will be used to examine selected problems such as the mechanics of subduction, the rise of mantle diapirs and generation of oceanic crust, postglacial rebound, postseismic rebound, generation and effects of anisotropy, mantle convection, and the driving mechanism for plate motions. Instructor: Gurnis. Given in alternate years; offered 2000–2001.

Ge 260. Physics of Earth Materials. *9 units (3-2-4); first term. Prerequisite: familiarity with basic concepts of thermodynamics and mineralogy; see instructor.* Application of high-pressure physics to geologic problems. Topics: concepts of elastic and shock propagation in single and polycrystalline solids and in fluids, and their relation to various thermodynamic processes; phase changes, dynamic yielding, shock metamorphism, high-pressure electrical properties of minerals, and application of shock and ultrasonic equation-of-state data to earth and planetary interiors. Instructors: Ahrens and Stock. Given in alternate years; offered 2000–2001. Additional information concerning this course can be found at http://www.gps.caltech.edu/~jstock/Ge260.html.

Ge 261. Advanced Seismology. *9 units (3-0-6); third term.* Continuation of Seismology with special emphasis on particular complex problems; includes generalizations of analytical methods to handle non-planar structures and methods of interfacing numerical-analytical codes in 2- and 3-dimensions; construction of earth models using tomographic methods and synthetics; requires a class project. Instructors: Helmberger and staff.

Ge 270. Continental Tectonics. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 or ACM 113; Ge 11 ab, Ge 106, Ge 166, Ge 180 or Ge 176.* Nature of non-plate, 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. Not offered 2000–2001.

Ge 276. Physics of Earthquakes. *9 units (3-0-6); third term. Prerequisite: ACM 95/100 abc or equivalent.* This course covers quantitative description of earthquake source, and details of physical processes involved in faulting. Rupture mechanics, physics of friction, and interaction with fluids will be discussed. Methods for earthquake source retrieval will be discussed with many examples and exercises. The concept of real-time seismology will be introduced and its engineering applications will be discussed with examples. Instructor: Kanamori.

Ge 277. Quaternary Tectonics Seminar. *6 units (1-3-2); second term.* Detailed analysis of one or more active tectonic regions, including discussion of published literature, and field examination. Not offered 2000–2001. Instructor: Sieh.

Ge 282 abc. Division Seminar. *1 unit; first, second, third terms.* Presentation of papers by invited investigators. In charge: Staff.

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.

GERMAN *(see Languages)*

These courses are open only to students who have fulfilled the freshman humanities requirement.

Hum/H 1 ab. The History of Qing China (1644–1912) and Tokugawa Japan (1600–1868) and the Rise of Contemporary East Asia. *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/SES 10 a. Introduction to the History of Science. *9 units (3-0-6). Offered by announcement.* For course description, see Humanities. Hum/H/SES 10 a may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement.

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 97 ab. Junior Tutorial. *9 units (2-0-7); second, third terms. Prerequisite: instructor's permission.* Designed for students majoring in history, with frequent meetings between instructor and student. Course subject matter varies according to individual needs. Normally taken junior year. Instructors: Staff.

H 98 ab. Senior Tutorial. *9 units (2-0-7); first, second terms. Prerequisite: instructor's permission.* Designed for students majoring in history, with frequent meetings between instructor and student. Normally taken senior year. Instructors: 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. Instructors: 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. Not offered 2000-2001. 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. Not offered 2000-2001. Instructor: Brown.

H 109. Protestant, Catholic, and Jew. *9 units (2-0-7).* Books both nonfiction and fiction that illuminate such topics in the political and social history of religion in Europe as Joan of Arc, Luther, the Spanish Armada, Victorian conformity, and the "final solution." Instructor: Fay. Not offered 2000-2001.

H 110. Early Modern Europe. *9 units (3-0-6).* Topics in the social, economic, political, and cultural history of Europe up to the 19th century. Topics may include the Renaissance, religious change, revolutions and warfare, and early industrialization. Instructor: Hoffman.

H 113. The Great War 1914–1945. *9 units (3-0-6).* How and why "The Great War" (as the two World Wars will probably come to be known) began, was fought, recessed in 1919, resumed in 1939, and ended at last, leaving Europe cruelly transformed and deeply divided. Attention will be equally divided between society, politics (including the Russian Revolution and Hitler), and the war itself. Instructor: Fay. Not offered 2000-2001.

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 120. Europe and Asia, 1500–1900. *9 units (3-0-6).* Episodes in Asia's penetration by Europeans in the course of these four centuries, and Asia's response; from Cairo to Canton; but with special attention to India. Instructor: Fay. Not offered 2000–2001.

H 124. Population and Family History. *9 units (3-0-6); third term.* Four aspects of population and family history in China and Europe: demographic, establishing the parameters of birth, marriage, and death; economic, treating the family as a unit of production as well as

consumption; social, analyzing the evolving structure of various kin groupings—lineage, clan, household, and family; cultural, identifying and interpreting the symbolic forms and meanings of the "family." Instructor: Lee. Not offered 2000–2001.

SES/H/Lit 128. British Science Fiction. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

H/Hum 130 ab. Cinema and Society. *9 units (2-2-5).* A two-term course that covers the history of world cinema from the 1890s to today. Focus will be on technological innovation, film language, stylistic change, and historical importance of film as it has developed in Europe, Hollywood, and the Third World. First term will cover from the origins of film through the 1940s, with emphasis on works from Hollywood, Germany, the Soviet Union, France, and Italy. Second term will cover from World War II to the present, and will include sections on Asia, East Europe, the Third World, and American independents. Students will view at least one feature film a week. Though the course is designed as a sequence, students may take a single term. Instructor: Rosenstone.

H/Hum 131. History on Film. *9 units (2-2-5). Offered by announcement.* 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 133. History of Ancient China, 2000 B.C.–1200 A.D. *9 units (3-0-6).* A systematic analysis of the growth and character of China from its early origins to the eve of the Mongol invasion. The characteristic development and unique features of pre-imperial and imperial China, including the periods of the first empire, disunion, and the second empire, will be examined in the context of how China developed into an enduring political and social entity. Not offered 2000–2001. Instructor: Lee.

H 134. History of Late Imperial China, 1200–1800. *9 units (3-0-6); third term.* An exploration of several major problems, including the growth of autocracy, population development, social mobility, and the Ming–Qing dynasty transition in the history of China, from the formation of the Mongol empire to the eve of the Opium War. Instructor: Lee. Not offered 2000–2001.

H 136. Family, Friendship, and Love in Chinese Culture. *9 units (3-0-6).* The nature of human relations in China. The purpose of the class is twofold: first, to introduce a number of selected texts on family, friendship, and love in Chinese culture; second, to provide a broad conceptual framework on self and society in traditional and contemporary China. Classes are organized around specific themes. Readings include anthropological, historical, and literary texts. Instructor: Lee.

H 139. Native America. *9 units (3-0-6); third term.* This course explores Native American history from contact to present. Emphasis upon demographic change, cultural accommodation and exchange, violence, and conquest. Course readings will include primary source material, Native American cultural and literary texts, various bureaucratic and official documentation of Indian wars and settlement contacts. Course will also explore changing dynamics of Native American incorporation into Anglo American legal tradition, ca. 1800–present. Instructor: Deverell. Not offered 2000–2001.

H 140. History of Los Angeles. *9 units (3-0-6).* A course that examines the 200-year history of Los Angeles through fiction, film, scholarship, and photography. Instructor: Deverell.

H 141. The 20th-Century American City. *9 units (3-0-6).* A survey course that examines the history of modern American urban development. Emphasis will be placed upon the social history of 20th-century American cities. Instructor: Deverell. Not offered 2000–2001.

H 142. History of California. *9 units (3-0-6); third term.* This course examines the history of California from the 16th century through the 20th century. Attention will be paid to demographic patterns of Native American and other peoples, exploration, colonization, extractive industries, and the political development of the state. Instructor: Deverell. Not offered 2000–2001.

H 143. Western Environmental History. *9 units (3-0-6); first term.* This course examines the history of the American West through the prism of environmental history. From discussion of Native American peoples and their interaction with the California environment through the demographic expansion of Anglo America in the 19th century and the environmental history of the 20th century, the course ranges broadly across time and California space. Instructor: Igler.

H 144. Topics in the History of American Immigration. *9 units (3-0-6).* A course that examines the history of American immigration from the 18th through the 20th centuries. This course will explore the impact of immigration upon American politics, culture, and law. Instructor: Deverell. Not offered 2000–2001.

H 145. Irish America. *9 units (3-0-6); second term.* Examination of trans-Atlantic migration, demographic, and political change, 1800–present. Course will explore dynamics of Irish American political traditions, influence of Irish republicanism on American politics, influence of American Civil War upon Irish American thought and culture, and rise of Irish voting blocs in the 20th century. Instructor: Deverell. Not offered 2000–2001.

H/PS 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. Not offered 2000–2001.

H 150 ab. African American History. *9 units (3-0-6).* This two-part course will explore the history of African Americans from 1600 to the present. Generally part *a* of the course will cover the African diaspora through Reconstruction; part *b* will cover the period since 1877. The first term is not a prerequisite for the second term. Instructor: Staff. Not offered 2000–2001.

H 152. America in the Era of Roosevelt and Truman. *9 units (3-0-6).* Topics in the history of the Depression, World War II, and the origins of the Cold War. Instructors: Kevles, Rosenstone. Not offered 2000–2001.

H 153 ab. America Since World War II. *9 units (3-0-6).* Topics in the recent social, cultural, and political history of the United States. First term is not a prerequisite for second term. Instructor: Kevles. Not offered 2000–2001.

H/SS 154 ab. Race Relations in History and Social Science. *9 units (3-0-6); second, third terms. Prerequisite: H/SS 154 a.* Approaches to racial and ethnic relations from both history and several of the social sciences (political science, sociology, social psychology, and economics) will be examined. The focus will be on the United States, but the experiences of other countries may be analyzed for comparative purposes. Why do people form distinctive groups, and why are some boundaries more permanent and impermeable than others? How have ethnic relations in the U.S. changed over time? Has the country entered a new, "colorblind" era of race relations? Instructor: Kousser.

SES/H 156. The History of Modern Science. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 157. Science in America, 1865–Present. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 158. The Scientific Revolution. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 159. Science and Society. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 160 ab. History of the Modern Physical Sciences. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

H 161. Selected Topics in History. *9 units (3-0-6). Offered by announcement.* Instructors: Staff, visiting lecturers.

SES/H 162. Social Studies of Science. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 163. Gender in the History of Science, Technology, and Medicine. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 164. Sciences of Mind and Society from the French Revolution to the Great War. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 165. History of Technology in the United States. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 166. The History of Environmentalism. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 168. The History of Modern Medicine. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/H 169. Selected Topics in Science, Ethics, and Society. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

Bi/H 171. The History of Your Science. *9 units (3-2-4).* For course description, see Biology.

H 201. Reading and Research for Graduate Students. *Units to be determined for the individual by the division.*

HUMANITIES

All courses numbered 1 through 20 are freshman humanities courses. Courses numbered above 99 are open only to students who have fulfilled the freshman humanities requirement.

Hum/H 1 ab. The History of Qing China (1644–1912) and Tokugawa Japan (1600–1868) and the Rise of Contemporary East Asia. *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 quarter is independent of the other, and students will normally take only one of the two quarters. Instructor: Lee.

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? Instructors: Deverell, Kevles, Kousser.

Hum/H 3 abc. European Civilization. *9 units (3-0-6). Offered by announcement.* This course will be divided into three quarters, each of which will focus on a coherent period in the history of European civilization. Each quarter is independent of the others, and students will normally take only one of the three quarters.

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 them access to their 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, Johns, Pigman, Winter.

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: Barkan, Rosenstone, Winter.

Hum/Lit 5. Major British Authors. *9 units (3-0-6). Offered by announcement.* This course will introduce students to the three most important genres of English literature—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. Instructor: Literature staff.

Hum/Lit 6. Major American Authors. *9 units (3-0-6). Offered by announcement.* This course will study major American authors from the 18th through 20th centuries, and students will be introduced to basic concepts of literary analysis. Authors may include Benjamin Franklin, Nathaniel Hawthorne, Emily Dickinson, Tennessee Williams, William Faulkner, Edith Wharton, and Toni Morrison. Students will be exposed to a variety of genres, including the novel, drama, and poetry. Instructor: Literature staff.

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. Instructors: 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. Instructors: Philosophy staff.

Hum/H/SES 10 a. Introduction to the History of Science. *9 units (3-0-6). Offered by announcement.* Major topics to be addressed include: 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/SES10a may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement. Instructors: History staff.

Hum/Pl/SES 10 b. Introduction to Philosophy of Science. *9 units (3-0-6).* Questions to be addressed include: What are scientific explanations? What are laws of nature? What are the methods used by scientists to evaluate their theories? Does science aim at providing true theories of the world? What factors theoretical, personal, or political contribute to theoretical changes? Is science wholly rational and objective? What kinds of ethical issues may be raised by current science and/or technology? Students will approach these questions through study of the works of great 20th century philosophers of science such as Carnap, Popper, Kuhn, and Feyerabend. Hum/Pl/SES 10 b may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement. Instructors: Philosophy staff.

Hum 119. Selected Topics in Humanities. *9 units (3-0-6). Offered by announcement.* Instructors: Staff, visitors.

SES/Hum 121. Freud. *9 units (2-0-7).* For course description, see Science, Ethics, and Society.

H/Hum 130 ab. Cinema and Society. *9 units (2-2-5).* For course description, see History.

H/Hum 131. History on Film. *9 units (2-2-5).* For course description, see History.

Hum 132. Humanities on Film. *3 units (1-1-1). Offered by announcement.* A mini-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. Instructor: Rosenstone.

Hum 133. Topics in Film History. *9 units (2-2-5). Offered by announcement.* Will focus each quarter 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.

Hum 140 ab. The History of the Book. *9 units (3-0-6). Offered by announcement.* A chronological survey of the evolution and cultural role of printed materials—specifically the book—in Western society from the 14th century to the present day. Instructors: Staff.

Hum 141 a. Offensive Literature. *9 units (3-0-6). Offered by announcement.* A survey of literature deemed at various historical periods to have been seditious, blasphemous, obscene, or libelous. Instructors: Staff.

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 200 for complete details.

JAPANESE *(see Languages)*

JET PROPULSION

Ae/JP 103 abc. Propulsion, Dynamics, and Control of Aircraft. *9 units (3-0-6).* For course description, see Aeronautics.

JP 121 abc. Jet Propulsion Systems and Trajectories. *9 units (3-0-6); each term. Open to all graduate students and to seniors with permission of instructor. Prerequisite: Ae/Me 120 a.* Modern aspects of rocket, turbine, 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, combustion instability. Subsonic and supersonic compressors and turbines, basic gas-turbine propulsion cycle and its variations, and inlets and diffusers. Instructors: Shepherd, Polk.

JP 131. Combustion Technology. *9 units (3-0-6); third term. Prerequisites: APh/ME 17 and ME 19.* Application of fluid dynamic and chemical principles to the study of combustion processes, including the theoretical and experimental treatment of laminar and turbulent flames; the combustion of liquid droplets and solid particles; and technical aspects of gas, oil, and coal combustion. Instructor: Culick. Not offered every year.

JP 213 abc. Dynamics of Reacting Gases. *9 units (3-0-6); each term. Prerequisites: APh/ME 17 abc; APh 101 abc or CE/ME 101 abc or equivalent.* Application of gas dynamic and chemical principles to the study of combustion processes, including theoretical and experimental treatment of laminar and turbulent flames; acoustic and detonation waves; volatilization and combustion of liquid droplets and solid particles; combustion problems of air-breathing engines and liquid- and solid-propellant rockets; flame stability; aspects of gas, oil, and coal combustion. Instructor: Culick. Not offered every year.

JP 270. Special Topics in Propulsion. *6 units (2-0-4); each term.* The topics covered will vary from year to year. Instructors: Staff.

JP 280. Research in Jet Propulsion. *Units to be arranged.* Theoretical and experimental investigations of problems associated with propulsion and related fields. Instructors: Staff.

LANGUAGES

L 101. Selected Topics in Language. *Units to be determined by arrangement with the instructor.* Graded pass/fail. Instructors: Staff, visiting lecturers.

L 102 abc. Elementary French. *10 units (3-1-6); first, second, third terms.* The course uses French in Action, a multimedia program, and emphasizes the acquisition of fundamental skills: oral ability, comprehension, writing, and reading. Students are evaluated on the basis of quizzes and compositions (1/3), midterm and final (1/3), and class participation (1/3). The course is mainly designed for students with no previous knowledge of French. Students who have had French in secondary school or college must consult with the instructor before registering. Instructor: Orcel.

L 103 abc. Intermediate French. *9 units (3-0-6); first, second, third terms. 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 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. French Literature. *9 units (3-0-6); second, third terms. Prerequisite: L 103 abc or equivalent.* Close critical analysis of representative works from 19th- and 20th-century authors. The texts are examined in relation to the artistic, intellectual, and political context. Designed for the non-specialist with little or no background in French literary history. Autobiography in 20th-century France, the modern French novel, the French avant-garde, the modern French theatre and its aesthetic, and woman's voices: 20th-century French narrative prose, are some of the topics offered previously. Film versions of the texts studied may be included. Conducted in French. Three 5-page critical papers on topics chosen by the student are required. Instructors: Orcel, de Bedts. *L 105a may be repeated for credit.*

L 106 abc. Elementary Japanese. *10 units (5-1-4); 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. Instructor: Hirai.

L 107 abc. Intermediate Japanese. *10 units (5-1-4); first, second terms. Prerequisite: L 106 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 1000 characters. Instructor: Hirata.

L 108 abc. Advanced Japanese. *10 units (3-1-6); first, second, third terms. Prerequisite: L 107 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 1850 "general-use characters." Instructor: Hirata.

L 110 abc. Elementary Spanish. *10 units (3-1-6); first, second, third terms.* Grammar fundamentals and their use in understanding, speaking, reading, and writing Spanish. Students who have had Spanish in secondary school or college must consult with the instructor before registering. Instructors: Garcia and staff.

L 112 abc. Intermediate Spanish. *9 units (3-0-6); first term. Prerequisite: L110 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 and staff.

L 114 abc. Topics in Spanish and Latin American Culture and Literature. *9 units (3-0-6). Offered by announcement. Prerequisite: L 112 abc or equivalent.* First term: Spanish "classical" literature of the 16th to the 18th centuries. Second term: Latin American literature of the 16th

to the 20th centuries. Third term: Contemporary topics in literature and/or film of the Hispanic world. Conducted in Spanish. Instructor: Garcia.

L 121 abc. Elementary Latin. *9 units (3-0-6).* The course aims to prepare students to read classical Latin. Instructor: Pigman. Not offered 2000–2001.

L 130 abc. Elementary German. *10 units (3-1-6); 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 quarters will emphasize written expression, technical/scientific translation, and literary readings. Students who have studied German elsewhere must consult with the instructor before registering. Instructor: Washburn.

L 140 abc. German Literature. *9 units (3-0-6). Prerequisite: L 132 abc or equivalent.* The reading and discussion of works by selected 19th- and 20th-century authors. Conducted in German. Instructor: Staff. Not offered 2000–2001.

L 141 abc. Elementary Russian. *10 units (3-1-6); first, second, third terms.* The course covers grammar and builds toward the capacity to understand, speak, read, and write Russian. Students who have had Russian in secondary school or college must consult with the instructor before registering. Not offered 2000–2001. Instructor: Staff.

L/Lit 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); first, second terms.* First term: French classical literature of the 17th and 18th centuries; second term: reading and discussion of works by selected 19th and 20th century authors. The approach is both historical and critical. Conducted in English, but students may read the French originals. Film versions of the texts studied may be included. Instructor: de Bedts.

L 153 abc. Intermediate Russian. *9 units (3-0-6); first, second, third terms. Prerequisite: L 141 abc or equivalent.* Grammar review, readings, discussion, and reports on material from Russian literature, culture, and history. Writing is emphasized in the second and third quarters. Instructor: Cheron.

L/Lit 160 ab. German Literature in Translation. *9 units (3-0-6).* First term: German literature of the 19th century—Biedermeier, Young Germany, Realism, and Naturalism; second term: "Tales of Hollywood," German Exile Literature 1933–45. Instructor: Washburn.

L/Lit 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/Lit 165 abc. Russian Literature in Translation. *9 units (3-0-6); first, second, third terms.* The development of Russian literature in its socio-historical context from the Classical period to contemporary texts. Authors will range from Pushkin to Solzhenitsyn. All readings in English. Instructor: Cheron.

L 166 abc. Russian Literature. *9 units (3-0-6); first, second, third terms. Prerequisite: L 153 or equivalent and permission of the instructor.* Reading and discussion of representative works of selected 19th- and 20th-century Russian authors. Conducted in Russian. Students are advised to take these courses in sequence. Instructor: Cheron. Not offered 2000–2001.

L 167 abc. Latin Literature. *9 units (3-0-6); first, second, third terms. Prerequisite: L 121 abc or equivalent.* Major works of Latin literature, usually one per term. No work will be studied more than once in four years, and students may repeat the course for credit. Instructor: Pigman. Not offered 2000–2001.

LATIN *(see Languages)*

LAW

Law 33. Introduction to the Law. *9 units (3-0-6); second 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: McCaffery.

Law 133. Topics in Anglo-American Law. *9 units (3-0-6); third term.* An introduction to the American legal system through the study of a particular sub-area of law, which may vary from term to term or year to year. Instructor: Staff. *May be taken more than once if the topic is different.*

These courses are open only to students who have fulfilled the freshman humanities requirement.

Hum/Lit 5. Major British Authors. *9 units (3-0-6).* For course description, see Humanities.

Hum/Lit 6. Major American Authors. *9 units (3-0-6).* For course description, see Humanities.

Lit 30. Reading in English. *Units to be determined for the individual by the division.* Collateral reading in literature and related subjects, done in connection with regular courses in literature or history, or independently of any course, but under the direction of members of the division. Graded pass/fail. Instructors: Staff. *Not available for credit toward humanities–social science requirement.*

Lit 85. Writing Poetry. *9 units (3-0-6).* 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. Enrollment is limited and upperclass undergraduates will be given priority. Students may apply one quarter of Lit 85, 86, 87, and 88 to the final 36-unit requirement of the division, and all other courses in this series will receive Institute credit. Instructors: Staff.

Lit 86. Writing Fiction: Realism. *9 units (3-0-6).* Students will develop their talents for writing short works of realistic fiction. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Enrollment is limited and upperclass undergraduates will be given priority. Students may apply one quarter of Lit 85, 86, 87, and 88 to the final 36-unit requirement of the division, and all other courses in this series will receive Institute credit. Instructors: Staff.

Lit 87. Writing Fiction: The Imaginary. *9 units (3-0-6).* 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. Enrollment is limited and upperclass undergraduates will be given priority. Students may apply one quarter of Lit 85, 86, 87, and 88 to the final 36-unit requirement of the division, and all other courses in this series will receive Institute credit. Instructors: Staff.

Lit 88. Writing Nonfiction. *9 units (3-0-6).* Students will develop their skills in handling various forms of nonfiction, such as the memoir, the critical review, the polemic, etc. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Enrollment is limited and upperclass undergraduates will be given priority. Students may apply one quarter of Lit 85, 86, 87, and 88 to the final 36-unit requirement of the division, and all other courses in this series will receive Institute credit. Instructors: Staff.

Lit 98. Tutorial for Literature Majors. *9 units (2-0-7). Prerequisite: instructor's permission.* An individual program of directed reading and research for literature majors in an area not covered by regular courses. Instructors: Staff.

Lit 99. Senior Tutorial for Literature Majors. *9 units (1-0-8); second term.* Students will study research methods, write a research paper, and make an oral presentation. Required of students in the literature option. Instructors: Staff.

Lit 100. Fundamentals of the Art of Poetry. *9 units (3-0-6).* 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 sensitive one? To illustrate the nature, functions, and resources of poetry, a wide-ranging selection of poems will be read and discussed. Instructor: Mandel.

Lit 110. Chaucer. *9 units (2-0-7).* Chaucer's major works, *Troilus and Criseyde,* and selections from *The Canterbury Tales.* Instructor: Pigman.

Lit 112 ab. English Renaissance Literature. *9 units (3-0-6).* The major genres and themes of English Renaissance literature from the Reformation of the early 16th century through the metaphysical poets of the 17th century. Instructors: La Belle, Pigman. Not offered 2000–2001.

Lit 114 ab. Shakespeare. *9 units (3-0-6). Offered by announcement. Not open to freshmen.* 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.

Lit 116. Milton. *9 units (2-0-7).* Milton's major works—*Paradise Lost, Paradise Regained,* and *Samson Agonistes*—and some of the prose and shorter poems. Instructor: Pigman. Not offered 2000–2001.

Lit 122 abc. The 18th-Century English Novel. *9 units (3-0-6); third term.* Development of the 18th-century novel from the early novelists through the end of the century, with emphasis upon understanding the formal developments of the novel in its historical context. Major

authors may include Defoe, Richardson, Fielding, Burney, Sterne, Radcliffe, Austen, Scott. Instructors: King and staff.

Lit 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, Bronte, Collins, Trollope, Stoker, Hardy. Instructors: King and staff.

Lit 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. Instructor: Staff.

Lit 125 ab. British Romantic Literature. *9 units (3-0-6); first term.* A selective survey of English writing in the late 18th and early 19th centuries. Major authors may include Blake, Wordsworth, Coleridge, Byron, Keats, Percy Shelley, Mary Shelley, and Austen. Particular attention will be paid to intellectual and historical contexts and to new understandings of the role of literature in society. Instructor: Gilmartin.

Lit 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: Gilmartin.

Lit 127. 19th-Century English Literature and Social Change. *9 units (3-0-6).* Course will explore literary responses to some of the central issues confronting English society in the 19th century: industrialization, the growth of cities, class tension, and shifting gender roles. Authors to be considered may include Shelley, Dickens, Gaskell, Eliot, Carlyle, Arnold, and Ruskin. Instructor: Gilmartin.

SES/H/Lit 128. British Science Fiction. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

Lit 129. Austen, Brontes, Woolf. *9 units (3-0-6); second term.* An introduction to four of the most important English writers of the 19th and early-20th centuries. Understanding these novelists as a tradition, we will pay particular attention to formal developments in the Novel, from the marriage plot to modernism. Jane Austen, Charlotte and Emily Bronte, and Virginia Woolf's major works—including but not limited to *Emma*, *Persuasion*, *Jane Eyre*, *Wuthering Heights*, *Mrs. Dalloway*, *To the Lighthouse*. Instructor: King.

Lit 131. Modern European Fiction. *9 units (2-0-7); third term.* French, German, and Italian novels and shorter fiction from the first half of the 20th century by authors such as Broch, Gide, Hesse, Kafka, Malraux, Thomas Mann, Musil, Proust, Schnitzler, and Svevo. Instructor: Pigman. Not offered 2000–2001.

Lit 132. American Literature Until the Civil War. *9 units (3-0-6); second term.* 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. Instructor: Weinstein. Not offered 2000–2001.

Lit 133. 19th-Century American Women Writers. *9 units (3-0-6); third 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: Weinstein.

Lit 134. The Career of Herman Melville. *9 units (3-0-6).* 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.

Lit 138. Twain and His Contemporaries. *9 units (3-0-6); third term.* Will study the divergent theories of realism that arose in the period after the Civil War and before WW 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 2000–2001. Instructor: Weinstein.

Lit 139. Birth of a Nation. *9 units (3-0-6).* American letters in the 18th century: This course will look at developing notions of national identity during the Revolutionary period and after. We shall study debates about authority in the nation, the place of gender, class, and race in the birth of the nation, and the relation between nationhood and literary narrative. Authors may include Jefferson, Franklin, Paine, Equiano, Rowson, Foster, William Hill Brown, and Charles Brockden Brown. Not offered 2000–2001. Instructor: Weinstein.

Lit 140. The Modern American Novel. *9 units (3-0-6).* Examines the development of the American novel from approximately 1917–1940. We will focus on the post-World War I literature of estrangement and exile, the Harlem Renaissance, and the proletarian

fiction of the Depression. Authors covered may include Willa Cather, F. Scott Fitzgerald, Ernest Hemingway, Nelson Algren, Zora Neale Hurston, and Richard Wright. Instructor: Jurca.

Lit 141. James and Wharton. *9 units (3-0-6); third term.* Covers selected novels, short fiction, and non-fiction writings of friends and expatriots Henry James and Edith Wharton. 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. We 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.* Instructor: Jurca.

Lit 145 ab. James Joyce and Modern Literature. *9 units (3-0-6).* Joyce's major works, along with selected poetry and fiction from his modernist contemporaries (Eliot, Yeats, Pound, Lawrence, Woolf, etc.). First term: through the opening chapters of *Ulysses.* Second term: the rest of *Ulysses* and selections from *Finnegan's Wake.* Instructor: Staff. Not offered 2000–2001.

Lit 147. American Assimilation Narratives. *9 units (3-0-6).* Will focus on 20th-century novels, short stories, and autobiographies that address the meaning and value of assimilation to American culture. Authors covered may include Abraham Cahan, Langston Hughes, Maxine Hong Kingston, Richard Rodriguez, Frank Chin, and Toni Morrison. Instructor: Jurca. Not offered 2000–2001.

Lit 148. Postwar Fiction and Film. *9 units (3-0-6); first term.* A study of postwar American culture through novels, short stories, and Hollywood films that will concentrate on the topics of social and economic reconversion, the rise of the "organization," suburbanization, and the Cold War. Authors covered may include J.D. Salinger, Phillip K. Dick, Laura Hobson, Jack Kerouac, and Norman Mailer. Film screenings may include *Mildred Pierce, Rebel Without a Cause, The Man in the Gray Flannel Suit, Invasion of the Body Snatchers,* and *The Manchurian Candidate.* Instructor: Jurca. Not offered 2000–2001.

Lit 149. Colonial Encounters. *9 units (3-0-6).* The literature and history of contact between Western European culture and those it defines as other, from Christopher Columbus to the present day. Attention to religion, race, and gender, and to European self-definitions in terms of other cultures. There will be readings also in non-European responses to colonization and empire. Authors may include Columbus, Cortés, Shakespeare, Rousseau, Kipling, Conrad, Aimé Césaire, David Henry Hwang, and Toni Morrison; films by Spike Lee and others. Instructor: Gilmartin.

L/Lit 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6).* For course description, see Languages.

L/Lit 160 ab. German Literature in Translation. *9 units (3-0-6).* For course description, see Languages.

L/Lit 162. Spanish and Latin American Literature in Translation. *9 units (3-0-6).* For course description, see Languages.

L/Lit 165 abc. Russian Literature in Translation. *9 units (3-0-6).* For course description, see Languages.

Lit 170. Drama from the Middle Ages to Molière. *9 units (3-0-6).* 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*. Instructor: Mandel.

Lit 171. Drama from Molière to Wilde. *9 units (3-0-6).* 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: Mandel.

Lit 172. Drama from Ibsen to Beckett. *9 units (3-0-6).* 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. Instructor: Mandel. Not offered 2000–2001.

Lit 180. Special Topics in Literature. *9 units (3-0-6). See registrar's announcement for details.* Instructor: Staff.

MATERIALS SCIENCE

Additional information concerning these courses can be found at http://www.caltech.edu/~matsci/classes.html.

MS 15 ab. Fundamentals of Materials Science. *9 units (3-0-6); first, second terms.* 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 relationship between chemical bonding, crystal structure, microstructure, and properties. Thermodynamics and phase equilibria are also discussed in this term. In the second term, generic processing

and manufacturing methods are presented for each class of materials. The emphasis is on the basic materials science behind each processing method. Kinetics of phase transformation are also covered in the second term. Instructors: Haile (first term); Üstündag (second term).

MS 90. Materials Science Laboratory. *9 units (1-6-2); third term. Prerequisites: MS 15 ab or instructor's permission.* An introductory laboratory in relationships between the structure and properties of materials. Experiments involve materials processing and characterization by X-ray diffraction, scanning electron microscopy, and optical microscopy. Students will learn techniques for measuring mechanical and electrical properties of materials, as well as how to optimize these properties through microstructural and chemical control. Independent projects may be performed depending on the student's interests and abilities. Instructor: Haile.

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.

MS 105. Phase Transformations. *9 units (3-0-6); third term. Prerequisites: 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. Instructor: Johnson.

MS 110 abc. Materials Research Lectures. *1 unit (1-0-0); first, second, third terms.* A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructors: Üstündag, Kornfield, Atwater.

MS 124. Mechanical Behavior of Materials. *9 units (3-0-6); third term. Prerequisites: AM 65 or instructor's permission.* Mechanical behavior of structural materials with emphasis on micromechanics of deformation in three generic regimes: elasticity, plasticity, and fracture. A materials science approach is followed to understand and model the mechanical behavior that combines continuum mechanics, thermodynamics, kinetics, and microstructure. Some topics include elastic properties of materials, permanent deformation mechanisms at different temperatures (e.g., via dislocation motion and creep), fracture in ductile and brittle materials, and prediction of composite properties as a function of component morphology. Specific classes of materials that are studied: metals, ceramics, polymers, composites, and glasses. Instructor: Üstündag.

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 131. Structure and Bonding in Materials. *9 units (3-0-6); first 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: Fultz.

MS 132. Diffraction and Structure of Materials. *12 units (3-3-6); second term. Prerequisites: MS 131 or instructor's permission.* 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 and 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.

APh/MS 140. Ion Beam Modification and Analysis of Materials. *6 units (2-0-4).* For course description, see Applied Physics.

APh/MS 141 bc. Microscopic Imaging, Diffraction, and Spectroscopy Laboratory. *9 units.* For course description, see Applied Physics.

MS 142. Application of Diffraction Techniques in Materials Science. *9 units (2-3-4); first 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. Instructors: Haile and Üstündag.

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 213 abc. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aeronautics.

MS 250 abc. Advanced Theory and Computation of the Properties of Materials. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 120 or Ch 121 or MS 131, or permission of the instructor.* First-principles techniques use fundamental physics and chemistry to predict and understand the behavior of materials, and are complementary to experimental studies. This course will consist of three parts: (a) lectures on methods and their applications, starting with fundamentals and working up to state-of-the-art techniques; (b) discussion seminars on the development of first-principles methods and current state-of-the-art studies from the literature; (c) computer laboratories to learn to use and develop computational methods, and critically analyze results of codes for computing materials properties. The emphasis will be on periodic bulk systems, but methods to study defects, sufaces, and interfaces will also be covered. Materials to be studied include those important at high pressures, geophysics, and technology, including electrically active materials such as ferroelectrics and naturally occurring minerals. A range of methods based on density functional theory will be studied for solving the electronic problem. For studying finite temperature properties, molecular dynamics, and Monte Carlo techniques using ab initio models and effective Hamiltonians will be included. Frontier issues will also be discussed, including how to treat systems with important electron correlation and path integral methods. Instructor: Cohen.

MS 300. Thesis Research.

MATHEMATICS

Ma 1 abc. Probability and Calculus of One and Several Variables. *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; basic probability. Complex numbers, Taylor polynomials, infinite series, basic 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 done in the regular Ma 1 a sequence. These students will not have probability in Ma 1 a and will be required to take Ma 1 d. Instructors: Simon, Aschbacher, Kechris, Ramakrishnan, Pandharipande.

Ma 1 d. Basic Probability. *5 units (2-0-3); third 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 any probability during Ma 1 a. It may not be taken by students who have passed the regular Ma 1 a. Instructor: Staff.

Ma 2 ab. Linear Algebra, Statistics, and Differential Equations. *9 units (4-0-5); first, second terms. Prerequisite: Ma 1 abc.* Linear algebra, basic statistics, ordinary differential equations. Instructors: Gabai, Wilson, Makarov, Flach.

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: 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: Ramakrishnan.

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: Kupin.

Ma 5 abc. Introduction to Abstract Algebra. *9 units (3-0-6); first, second, third terms. Freshmen must have permission of the instructor 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: Wales, Baranovsky.

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 permission of the instructor.* First term: a survey emphasizing graph theory, algorithms, and applications of algebraic structures. Graphs: paths, trees, circuits, breadth-first and depth-first search, 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, Kechris.

Ma 8 a. 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 and probability. Ma 8 bc will be given if there is sufficient student demand. Instructors: Staff.

Ma 10. Oral Presentation. *3 units (2-0-1); first term. Open for credit to anyone. Freshmen must have permission of instructor 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 will also be elementary lectures from members of the mathematics faculty on topics of their own research interest. Instructor: Wales.

Ma 12. Chance. *9 units (4-0-5); third term.* This course will explore the use and misuse of notions of probability and statistics in popular culture and in science. The course will be structured around case studies chosen from mass media and from the scientific literature. Instructor: Lorden.

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. Graded pass/fail. Instructor: Staff.

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 108 abc. Classical Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 2 or equivalent, or consent of the instructor. May be taken concurrently with Ma 109.* First term: structure of the real numbers, topology of metric spaces, a rigorous approach to differentiation

in $\mathbb{R}^n$. 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: Hundertmark, Keel.

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: Belegradek, Givental.

Ma 110 abc. Real and Complex Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 108 or equivalent.* First term: linear topology: topological and metric spaces, topological vector spaces, Hilbert and Banach spaces, duality, convexity. Measure theory: measure spaces, integral, L^p-spaces, extensions of measures, measures in topological spaces, measures as functionals. Second term: Real analysis: Lebesgue measure in $\mathbb{R}^d$, change of variables, covering theorems, maximal functions, differentiation of measures and functions, Hausdorff measures, arc length and surface measures, integral and convolution operators, L^p-estimates, interpolation theorems, singular intervals, generalized functions, Sobolev spaces. Harmonic analysis: Fourier analysis of periodic functions, harmonic functions in the unit disc and Fourier series, harmonic analysis in $\mathbb{R}^d$, Fourier integral, boundary behavior of harmonic functions, convergence of Fourier series and integrals, applications to analysis of convolution operators. Third term: complex analysis: elementary theory of analytic functions, H^p-spaces, Hilbert transform, functions of several complex variables, entire and meromorphic functions, Fourier integral on the complex plane. Instructors: Kupin, Farag.

Ma 112 ab. Statistics. *9 units (3-0-6); first and second terms. Prerequisite: Ma 1 a probability and Ma 2 a 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. Instructor: Lorden.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or consent of instructor.* 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. Not offered 2000–2001.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or consent of instructor.* 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. Instructor: Gao.

Ma 118 a. Topics in Mathematical Logic. *9 units (3-0-6); first term. Prerequisite: Ma 116 or Ma 117 or equivalent.* Topics to be chosen from model theory and its applications, infinitary logic and admissible sets, ordinary and generalized recursion theory, consistency and independence results in set theory, large cardinals, descriptive set theory. Contents vary from year to year so that students may take the course in successive years. Not offered 2000–2001.

Ma 120 abc. Abstract Algebra. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent.* 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, Dee.

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. Instructor: Yu.

Ma 122 ab. Topics in Group Theory. *9 units (3-0-6); first, second terms. Prerequisite: Ma 5 or consent of instructor.* Modern theory of finite permutation groups: Structure of primitive groups, maximal subgroups of the symmetric and classical groups, subgroups of groups of Lie type. Not offered 2000–2001.

Ma 123. Classification of Simple Lie Algebras. *9 units (3-0-6). 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 2000–2001.

EE/Ma 126 ab. Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ma 127 abc. 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.* For course description, see Computer Science.

Ma 130 abc. Algebraic Geometry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 120 (or Ma 5 plus additional reading).* Plane curves, rational functions, affine and projective varieties, products, local properties, birational maps, divisors, differentials, intersection numbers, schemes, sheaves, general varieties, vector bundles, coherent sheaves, curves and surfaces. Instructor: Polito.

Ma 140 ab. Functional Analysis. *9 units (3-0-6); second, third terms. Prerequisite: Ma 110.* Second term: Theory of operators. Third term: Symmetric and selfadjoint operators, spectral analysis of differential operators. Not offered 2000–2001.

Ma/ACM 142 ab. Ordinary and Partial Differential Equations. *9 units (3-0-6); 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. Instructor: Staff.

Ma/ACM 144 ab. Probability. *9 units (3-0-6); second, third 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. Not offered 2000–2001.

Ma 145 ab. Introduction to Unitary Group Representations. *9 units (3-0-6); first, second 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. General representation theory of finite groups. Frobenius's theory of representations of semidirect products. The Young tableaux and the representations of symmetric groups. The Peter-Weyl theorem. The classical compact groups and their representation theory. Weyl character formula. Instructor: Simon.

Ma 147 ab. Dynamical Systems. *9 units (3-0-6); second, third terms. Prerequisite: Ma 108, Ma 109, or equivalent.* Second term: Ergodic theory. Third term: real and complex dynamics. Instructor: Makarov.

Ma 148 a. Topics in Mathematical Physics. *9 units (3-0-6); first term.* The course will discuss the moment problem, inverse spectral theory for one-dimensional Schrödinger operators, and the connections between them. May be taken for credit in multiple years. Not offered 2000–2001.

Ma 151 abc. Topology and Geometry. *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, cohomology and calculation of homology groups, exact sequences. Fibrations, higher homotopy groups and exact sequences of fibrations, structure of differentiable manifolds, degree theory, De Rham cohomology, elements of Morse theory. Geometry of Riemannian manifolds, covariant derivatives, geodesics, curvature, relations between curvature and topology. Instructors: Gabai, Belegradek, Pandharipande.

Ma 157 ab. Geometry and Topology of Manifolds. *9 units (3-0-6); second term. Prerequisite: Ma 151 or equivalent.* The relationship between the hyperbolic geometry of two- and three-dimensional manifolds and their underlying topology. Course content varies widely from year to year so that students may take the course in subsequent years. Ma 157 b not offered 2000–2001. Instructor: Gabai.

Ma 160 abc. Number Theory. *9 units (3-0-6); first, second, 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. Instructor: Dee. Ma 160 c not offered 2000–2001.

Note: The courses labeled Ma 191 are one-shot courses reflecting the interests of faculty, visitors, and students. Other Ma 191 titles may be announced.

Ma 191 a. Étale Cohomology. *9 units (3-0-6); first term. Prerequisite: Ma 130 abc, including a working knowledge of schemes.* The course treats cohomology theories for schemes other than the cohomology of coherent sheaves explained in any introductory algebraic geometry course. The notion of a Grothendieck topology will be introduced and then specialized to the case of the étale topology. The aim is to cover the basic theorems such as smooth and proper base change, as well as give connections to arithmetic. Instructor: Flach.

Ma 191 b. Galois Representations. *9 units (3-0-6); first term. Prerequisite: Ma 120 abc (in particular, the basic notations of representation theory) plus rudiments of number theory.* This course will cover some of the basic material on finite-dimensional representations of Galois groups. The first part of the course will cover complex representations, which amounts to studying finite Galois groups. Here the stress will be on the notion of the conductor, along with the definition and proper-

ties of Artin L-functions. The second part of the course will deal with ell-adic representations; particular attention will be paid to the symmetric powers of the two-dimensional representation associated to an elliptic curve over the rationals. Instructor: Ramakrishnan.

Ma 191 c. Complex Tori and Abelian Varieties. *9 units (3-0-6); first term.* The class will be an introduction to the theory of complex abelian varieties. Topics will include projective embeddings of an abelian variety, Jacobians and Prym varieties linked to the theory of algebraic curves, complex tori, Theta functions, cohomology of line bundles, and moduli problems. Instructor: Pandharipande.

Ma 191 d. p-adic Hodge Theory. *9 units (3-0-6); second term. Prerequisite: Ma 191 a (Étale Cohomology).* It is known that the singular cohomology of varieties over the complex number has more structure than what one would just expect from topology—it has a so-called Hodge structure. p-adic Hodge theory establishes similar structures in the étale cohomology of varieties over local fields. The course will lead up to the basic theorem of the subject: the comparison between étale and de Rham cohomology. Instructor: Flach.

Ma 191 f. Analytic Number Theory. *9 units (3-0-6); second term. Prerequisite: Ma 108 abc.* In this course we will mainly be interested in the theory of the Riemann zeta function: its analytic properties; functional equation; asymptotics; mean-value theorems; its zeros in the critical strip; and the hypotheses of Riemann and Lindelöf, along with some of their consequences. Instructor: Farag.

Ma 191 g. Geometric Invariant Theory. *9 units (3-0-6); second term.* The course introduces geometric invariant theory, a basic tool in algebraic geometry, which allows one to construct varieties parametrizing families of geometric objects (such as curves, vector bundles, etc.). The topics to be covered will include linearizations of actions, stable and semistable points, Hilbert-Mumford criterion, moment map and connections to symplectic and hyper-Kähler geometry, dependence on the choice of linearization. Various geometric examples will be considered in detail. Instructor: Baranovsky.

Ma 191 h. Automorphic Forms. *9 units (3-0-6); third term. Prerequisite: Ma 110 and Ma 120.* Automorphic functions arose in the 19th century at the crossroads of number theory, complex analysis, and discrete groups. This course will provide an introduction, with the arithmetic aspects in mind, and will present the representation-theoretic point of view. Instructor: Ramakrishnan.

Ma 191 i. Introduction to Schrödinger Operators. *9 units (3-0-6); third term.* An introduction to the mathematical theory of Schrödinger operators (called Hamiltonians in quantum mechanics courses). The course will mainly cover the basic facts, such as criteria for self-adjointness of operators and some aspects of the spectral theory for decaying and periodic potentials. Additional topics, such as multi-particle systems, may be included. Instructor: Hundertmark.

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. Instructors: Aschbacher, Wales.

Ma 345 abc. Seminar in Analysis. Instructors: Makarov, Staff.

Ma 348 abc. Seminar in Mathematical Physics. Instructor: Simon.

Ma 351 abc. Seminar in Topology. Instructor: Gabai.

Ma 360 abc. Seminar in Number Theory. Instructors: Flach, 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 applied mechanics, applied physics, jet propulsion, and materials science.

ME 18 ab. Thermodynamics. *9 units (3-0-6); first, second terms.* An introduction to classical thermodynamics with engineering applications. The first quarter includes: first and second laws; closed and open systems; properties of a pure substance; availability and irreversibility; generalized thermodynamic relations. Second quarter emphasizes applications: gas and vapor power cycles; propulsion; mixtures; combustion and thermochemistry; chemical equilibrium. Instructor: Shepherd.

ME 19 abc. Fluid Mechanics and Gasdynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2, Ph 1 abc.* Basic equations of fluid mechanics, theorems of energy, linear and angular momentum, potential flow, elements of airfoil theory. Flow of real fluids, similarity

parameters, flow in closed ducts. Boundary-layer theory in laminar and turbulent flow. Introduction to compressible flow. Flow and wave phenomena in open channels. Additional topics may include those related to energy production and conversion, and heat transfer phenomena, at the instructor's discretion. Instructor: Raichlen.

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. Instructors: Staff.

ME 70. Introduction to the Kinematics of Mechanical Systems. *9 units (3-0-6); second term. Prerequisites: none.* Introduction to the study of planar, rotational, and spatial rigid body motions with applications to linkages and mechanisms. Topics include dimensional synthesis of planar linkages; theory of gears and cams; and screw theory and its application to mechanism analysis. Instructor: Staff.

ME 71. Introduction to Engineering Design. *9 units (3-5-1); third term. Prerequisites: AM 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: Burdick.

ME 72. Engineering Design Laboratory. *12 units (3-8-1); first term. Prerequisites: AM 35 abc, ME 71, or equivalent and permission of instructor. 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.* The design process in engineering, stressing the creative aspects, especially problem definition, and concept generation, as well as visual thinking and graphical communication. Techniques in analysis of engineering systems learned previously will be reviewed and applied. An engineering design contest will be held, and will include the design, fabrication, and operation of a device to compete with similar devices designed by other students. These laboratory units of ME 72 can be used to fulfill a portion of the laboratory requirement in the Engineering and Applied Science division. Instructor: Antonsson.

ME 73. Machine Component Design. *9 units (3-4-2); second term. Prerequisites: AM 35 abc, ME 72, or permission of instructor.* 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. Instructor: Staff. Not offered 2000–2001.

ME 90 abc. Senior Thesis, Experimental. *9 units; (0-0-9) first term; (0-9-0) second and 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: Culick.

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: Culick.

ME/CE 96. Mechanical Engineering Laboratory. *6 or 9 units as arranged with instructor; third term. Prerequisites: ME 18 ab, ME 19 ab, AM 35 ab.* A laboratory course in the experimental techniques for heat transfer, fluid mechanics, solid mechanics, and dynamics. Students usually select approximately three regular experiments, but they may propose special investigations of brief research projects on their own. Instructors: Staff.

CE/ME 97. Fluid Mechanics Laboratory. *6–9 units as arranged with instructor.* For course description, see Civil Engineering.

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 Aeronautics.

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. Instructors: Staff.

ME 115 ab. Introduction to Kinematics and Robotics. *9 units (3-0-6); first and second 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 119 abc. Heat Transfer and Thermodynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 18, ME 19, ME 20, ACM 95/100 or equivalent, Ae/APh/CE/ME 101 abc (may be taken concurrently).* The first term covers the fundamentals of classical and statistical thermodynamics. Topics include: basic postulates, thermodynamic potentials, work and heat, chemical equilibrium, phase transitions, and the thermodynamic properties of solids, liquids, and gases. The second and third terms focus on heat, mass, and momentum transfer. Topics include: transport properties, conservation equations, conduction heat transfer in solids, convective heat, mass, and momentum transport in laminar and turbulent flows, phase change processes, thermal radiation, and selected engineering applications. Instructor: Hunt.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6).* For course description, see Aeronautics.

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: Burdick. Not offered 2000–2001.

ME 132. Advanced Robotics: Navigation and Vision. *9 units (3-6-0); third 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: Burdick. Not offered 2000–2001.

ME 170. Introduction to Mechanical CAD. *4 units (1-0-3); third term. Prerequisites: none.* An introduction to the use of one or more mechanical computer-aided design (CAD) packages via a series of weekly instructional exercises. Instructor: Antonsson.

ME 171. Computer-Aided Engineering Design. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 abc, AM 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. Instructor: Antonsson.

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. Instructor: Antonsson. Not offered 2000–2001.

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 2000–2001.

ME 206 ab. Acoustic Waves in Fluids. *9 units (3-0-6); first, second terms. Prerequisites: ACM 95/100 abc, AM 125 abc (may be taken concurrently), or equivalent. Recommended prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* This course stresses the fundamentals of acoustic wave motion in gases, especially the interactions of acoustic waves with flows and solid boundaries, and the generation of acoustic waves by turbulence. Analogies with electromagnetics, water waves, geophysics, and other fields will be discussed. Emphasis will be given to various analytical and computational techniques for solving wave equations, but practical results relevant to engineering devices will also be discussed. *First term:* Review of the equations of motion, thermodynamic relations, constitutive relations; review of Fourier analysis; the speed of sound; small amplitude disturbances and the equations of linear acoustics; compact source regions and multipole expansions; sound from radiating bodies; wave guides and lumped-parameter models of sound transmission; acoustic energy and intensity; dissipative effects; nonlinear

effects in sound propagation, shock waves, and sonic booms. *Second term:* Low-frequency scattering from bodies and flow inhomogeneities; geometrical acoustics, diffraction, and caustics; sound generation by turbulence; acoustic analogy theories; subsonic and supersonic jet noise; vortex sound theory; computational methods in acoustics; nonreflecting boundary conditions. Not offered 2000–2001.

ME 219. Advanced Topics in Thermal Sciences. *Prerequisite: ME 119 or consent of instructor.* Current topics in thermal sciences research. Course content will depend on interests of students and instructor. Instructors: Staff. Not offered 2000–2001.

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

These courses are open only to students who have fulfilled the freshman humanities requirement.

Mu 101. Selected Topics in Music. *Offered by announcement. Units to be determined by arrangement with instructor.* Instructors: Staff, visiting lecturers.

EE/Mu 107 abc. Projects in Music and Science. *Units to be individually arranged, up to a maximum of 12.* For course description, see Electrical Engineering.

Mu 121. 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 122. Form and Style in Music. *9 units (3-0-6); second term.* The Listening Experience II. One or more major genres (i.e., symphony, concerto, opera, etc.) will be traced through several periods of music history. Course will include guided listening and analysis intended to deepen the students' understanding of various composers' approaches to similar forms of musical expression. Instructor: Neenan. Not offered 2000–2001.

Mu 123. Major Figures. *9 units (3-0-6); third term.* A major personality in the history of music (i.e., Bach, Mozart, Beethoven) will be studied in depth. Course to be coordinated with major off-campus con-

certs, commemorations, and other events. Specific course content to be announced prior to registration. Instructor: Neenan. Not offered 2000–2001.

Mu 127. Fundamentals of Music Theory and Elementary Ear Training. *9 units (3-0-6). No prerequisite.* 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 128. Harmony I. *9 units (3-0-6). Prerequisite: Mu 127 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 129. Harmony II. *9 units (3-0-6). Prerequisite: Mu 128 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 131. Music of Courts and Cathedrals. *9 units (3-0-6).* Explores the music of the Middle Ages and Renaissance, including that of the great medieval monasteries, cathedrals, and chapels. Will include study of the music and dances from courts, towns, and countryside by trouveres, troubadours, and other entertainers. Instructor: Neenan. Not offered 2000–2001.

Mu 132. Monteverdi to Bach: Music of the Baroque. *9 units (3-0-6).* Survey of musical forms and composers during the period 1600–1750. To include masterworks of Monteverdi, Purcell, Vivaldi, Handel, Bach, and others. Instructor: Neenan.

Mu 133. Music of the Age of Enlightenment. *9 units (3-0-6).* Music of the so-called "pre-Classic" and "Classic" periods (ca. 1750–1825), with emphasis on C. P. E. Bach, Gluck, Haydn, Mozart, and the early works of Beethoven. Instructor: Neenan.

Mu 134. Music of the Early Romantics. *9 units (3-0-6); first term.* Romanticism in music during the early 19th century. Examines a wealth of music from late Beethoven to Schubert, Berlioz, Chopin, Mendelssohn, Schumann, and Liszt. Instructor: Neenan. Not offered 2000–2001.

Mu 135. Music of the Late Romantics. *9 units (3-0-6); second term.* An exploration of the music of the late 19th century. Included will be nationalist composers: Dvorak, Mussorgsky, and Grieg; major symphonists: Brahms, Bruckner, and Mahler; and opera composers: Verdi, Wagner, and Puccini. Instructor: Neenan. Not offered 2000–2001.

Mu 136. Music of Our Time. *9 units (3-0-6); third term.* The diversity of music in the 20th century will be explored. Included will be music of composers from Stravinsky, Schoenberg, and Bartok to John Adams and Phillip Glass. Course will include music for film, electronically generated music, and a field trip to an electronic music studio. Instructor: Neenan. Not offered 2000–2001.

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. Instructors: Staff.

PA 20 abc. Debate. *3 units (1-0-2); first, second, third terms.* Study and discussion of the annual intercollegiate debate topic. Instructors: Staff.

PA 30 abc. Women's Glee Club. *3 units (0-3-0); first, second, third terms.* Study and performance of the choral repertoire for women's voices encompassing all styles, all periods. Includes both group and individual instruction as well as on-campus and off-campus performances. Three hours per week. No previous experience required. PA 30 a or PA 30 b required to enroll in PA 30 c. Instructor: LaVertu.

PA 31 abc. Chamber Music. *3 units (0-3-0); first, second, third terms.* Study and performance of music for mixed ensembles of three to seven members and for piano four-hands. Literature ranges from the Baroque to contemporary eras. Open to students who play string, woodwind, brass instruments, or piano. After auditioning, pianists will be placed in either section by the instructors.
Section 1: Mixed ensembles. Instructor: D. Bing.
Section 2: Piano four-hands. Instructor: Gross.

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,and third terms.* Study and performance of all styles of jazz music, from Duke Ellington to Pat Metheny. Jazz improvisation is also stressed. Instructor: W. Bing.

PA 35 abc. Guitar. *3 units (0-3-0); first, second, and third terms.* Offered on three levels: beginning (no previous experience required), intermediate, and advanced. Instruction in a strong classical technique, including an exploration of various styles of guitar—classical, flamenco, folk, and popular. Instructor: Denning.

PA 36 abc. Men's Glee Club. *3 units (0-3-0); first, second, third terms.* Performance of repertoire from the Renaissance to the present day for men's voices in all styles. Opportunity for performance with orchestra and for mixed voices. No prerequisite or previous experience necessary. Three hours of rehearsal a week. Individual instruction. Instructor: Caldwell.

PA 37 abc. Chamber Singers. *3 units (0-3-0); first, second, third terms.* A sixteen-voice SATB auditioned ensemble, the Chamber Singers provide costumed entertainments for the Athenaeum and community in December, participate with orchestra in the annual All-Mozart Concert in April, and present a musical theatre review in June. One and a half hours of rehearsal per week. Instructor: Caldwell.

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, as well as a few relevant field trips offered as possible. 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: Marneus.

PA 50 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. Instructors: Staff.

PA 61 abc. Silkscreen and Airbrush. *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-life 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 slab roller and potter's wheel, and glazing methods. Instructor: Freed.

PHILOSOPHY

These courses are open only to students who have fulfilled the freshman humanities requirement.

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.

Hum/Pl/SES 10 b. Introduction to the Philosophy of Science. *9 units (3-0-6). Offered by announcement.* For course description, see Humanities. Hum/Pl/SES 10 b may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement.

Pl 30. Reading in Philosophy. *Units to be determined by the instructor. Elective in any term.* Reading in philosophy, done either in connection with the regular courses or independently of any course, but under the direction of members of the department. One or more short papers may be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* Instructors: Staff, visiting lecturers.

SES/Pl 123. Causation and Explanation. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 125. Introduction to Philosophy of Biology. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 126. Biomedical Ethics. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 127. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7).* For course description, see Science, Ethics, and Society.

SES/Pl 131. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 132. Philosophy and Biology. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 133. Philosophy of Physics. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 135. Current Issues in Philosophical Psychology. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

Pl 150. History of Early Modern Philosophy. *9 units (3-0-6). Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* A study of important figures and ideas in the empiricist and rationalist traditions in the period from Descartes through Kant. Material covered will vary depending on the decision of the instructor, but will include readings from some of the following: Descartes, Spinoza, Leibniz, Kant, Hobbes, Locke, Berkeley, and Hume. Instructor: Cowie. Not offered 2000–2001.

SES/Pl 169. Selected Topics in Science, Ethics, and Society. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

SES/Pl 185. Moral Philosophy. *9 units (3-0-6).* For course description, see Science, Ethics, and Society.

PHYSICAL EDUCATION

PE 1. Student Designed Fitness. *3 units.* Independent fitness program as arranged with instructor, three times a week. Proposals must be submitted in writing during first week of each term. Instructor: D'Auria.

PE 2. Skin Diving. *3 units. A prerequisite for PE 3 (Scuba).* Fundamentals of skin diving and oceanography. Instructor: Dodd.

PE 3. Scuba, Beginning. *3 units. Prerequisite: PE 2.* Open Water Scuba Diving will involve classroom instruction on diving physics, physiology, water safety, equipment, and oceanography. There will be confined water training (pool), and open water training consisting of two dives from a local beach and two dives from a boat. A third trip will be to conduct snorkeling. Students must pass a difficult swim test (see instructor for men's and women's qualifying standards) prior to enrollment. Instructor: Dodd.

PE 4. Introduction to Power Walking. *3 units.* Introduction to walking for fitness. Emphasis on cardiovascular benefits for a healthy lifestyle. The program is progressive and suitable for walkers of all levels. Not offered 2000–2001.

PE 5. Fitness Training for Life. *3 units.* Sets up and implements individually based fitness training programs for each student while concurrently teaching the modern fundamentals of a healthy lifestyle. Instructor: Staff.

PE 9. 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: Madsen.

PE 10. 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. 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/include students who don't fit criteria. Instructor: D'Auria.

PE 14. 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: Victor, Madsen.

PE 20. Fencing, Beginning and Intermediate/Advanced. *3 units.* Introduction to Fencing to include 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: Clovis.

PE 23. Track and Field, Beginning. *3 units.* Features instruction on ten different track events, allowing the student an opportunity to attempt a variety of skills to include: 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. 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 non-competitive 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. Instructors: Staff.

PE 27. Ultimate Frisbee. *3 units.* Instruction will center on developing student's knowledge of techniques, rules, strategy, etiquette, and safety regulations of the game. Students will develop the ability to perform all skills necessary to play the game confidently on a recreational basis. Instructors: Landesman, Boortz.

PE 30. 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. 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. 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. Water Polo. *3 units.* Basic recreational water polo with instruction of individual skills and team strategies. A swimming background is encouraged. Instructor: Dodd.

PE 44. 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 additional requirement of memorizing one or more simple kata (forms). Instructor: Staff.

PE 46. Karate (Tang Soo Do), Beginning and Intermediate/Advanced. *3 units.* Korean martial art focusing on self-defense and enhancement of physical and mental health. Practical and traditional techniques such as kicks, blocks, hyungs (forms) are taught. Intermediate/Advanced level incorporates technique combinations, sparring skills, jumping and spinning kicks, and history and philosophy. Instructor: Staff.

PE 48. T'ai-Chi Ch'uan, Beginning and Intermediate/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. 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. 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. Instructors: D'Auria, Levesque.

PE 56. 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. Tennis; Beginning, Beginning/Intermediate, 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, Nelson, and staff.

PE 70. 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 to various methods, terminology, and techniques in the areas of isokinetic strength and cardiovascular fitness training. Instructors: D'Auria, Victor, Madsen.

PE 77. 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 82. 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 climbing wall and then later at off-campus climbing site. Intermediate level will include ascents on prussiks or jumars, with more off-campus climbing. Instructor: Staff.

PE 84. 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. Multi-ball exercise with robot machines and video utilized. 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. Intercollegiate Basketball Team (Women). *3 units.* Coach: Madsen.

PE 85. Intercollegiate Track and Field Team. *3 units.* Coach: Levesque.

PE 87. Intercollegiate Swimming Team (Men and Women). *3 units.* Coach: Dodd.

PE 89. Intercollegiate Fencing Team (Men and Women). *3 units.* Coach: Clovis.

PE 90. Intercollegiate Water Polo Team (Men). *3 units.* Coach: Dodd.

PE 91. Intercollegiate Basketball Team (Men). *3 units.* Coach: Victor.

PE 92. Intercollegiate Soccer Team (Men). *3 units.* Coach: Levesque.

PE 93. Intercollegiate Baseball Team (Men). *3 units.* Coach: D'Auria.

PE 94. Intercollegiate Golf Team (Men). *3 units.* Coach: TBA.

PE 95. Intercollegiate Tennis Team (Men). *3 units.* Coach: Gillam.

PE 96. Intercollegiate Tennis Team (Women). *3 units.* Coach: Nelson.

PE 97. Intercollegiate Cross Country Team (Men and Women). *3 units.* Coach: Jung.

PE 99. Intercollegiate Volleyball Team (Women). *3 units.* Coach: TBA.

PHYSICS

Ph 1 abc. Classical Mechanics and Electromagnetism. *9 units (4-0-5); first, second, third terms.* The first year of a two-year course in introductory classical and modern physics. Topics: Newtonian mechanics in Ph 1 a; electricity and magnetism, and special relativity, in Ph 1 b, c. Emphasis on physical insight and problem solving. Ph 1 b, c is divided into two tracks: the Practical Track emphasizing practical electricity with take-home lab kits, and the Analytic Track, which has no lab component but teaches and uses methods of multivariable calculus. Students will be given information helping them to choose a track at the end of fall quarter. Lecturers: Filippone, McKeown, Politzer. Section leaders: Cohen, Djorgovski, Eisenstein, Newman, Phillips, Pine, Politzer, Prince, Soifer, Roukes.

Ph 2 ab. Statistical Physics, Waves, and Quantum Mechanics. *9 units (4-0-5); first, second terms. Prerequisites: Ph 1 abc, Ma 1 abc, or their equivalents.* The second year of a five-term introductory course in classical and modern physics. Topics to be covered include statistical physics and classical waves first term, introductory quantum mechanics second term. Lecturers: D. Goodstein, Martin.

** Students may transfer from Ph 12 b to Ph 2 b any time during the quarter, before the last day for dropping courses. The final grade will be based on the combined record in the two courses.*

Ph 3. Physics Laboratory. *6 units; first, second, third terms. Prerequisite: Ph 1 a, or permission of the instructor.* One three-hour laboratory session per week, an individual conference with the instructor, prelab preparation, and analysis of experimental results outside the laboratory period. This introductory course emphasizes quantitative measurements, the treatment of measurement errors, and graphical analysis. A variety of experimental techniques will be employed: studies of d.c. meters, the oscilloscope, the Maxwell top, electrical and mechanical resonant sys-

tems, and radioactivity. The content of each term is identical and only one term may be taken for credit. Freshmen/sophomores graded pass/fail; upper-class students receive letter grades, except with instructors' permission. Instructors: Skelton, Zmuidzinas.

Ph 5. Physics Laboratory. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or their 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: Skelton, Zmuidzinas.

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: Skelton, Zmuidzinas.

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: Skelton, Zmuidzinas.

Ph 10 ab. Frontiers in Physics. *3 units (2-0-1); first, second terms. 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: Barish.

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. May be taken to fulfill the Institute Ph 2 requirement. Instructors: Weinstein, Kimble. Additional information concerning this course can be found at http://www.its.caltech.edu/~ajw/ph12.html.

** Students may transfer from Ph 12 b to Ph 2 b any time during the quarter; before the last day for dropping courses. The final grade will be based on the combined record in the two courses.*

Ph 20, 21, 22. Freshman/Sophomore 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. Instructor: Prince.

20. *6 units (0-6-0); first, second, third terms. Prerequisite: CS 1 or equivalent experience in programming.* Introduction to scientific computing with applications to physics. Use of simple 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 simple 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 simple numerical techniques.* Introduction to scientific computing on parallel computers. Introduction to parallel computing and multi-processing. Message passing on networked workstations. Algorithm decomposition and parallelization. Numerical solution of N-body systems on multi-processor computers. Additional information concerning this course can be found at http://tweedledee ~physlab/.

Ph 70. Oral Presentation. *3 units; second, third terms; limited enrollment.* A seminar on physics topics of contemporary interest, with emphasis on organization and communication. Intended to provide guidance and practice in the effective oral presentation of scientific material. Instructor: Hitlin.

Ph 76. Atomic/Laser Physics Laboratory. *9 units; first, second, third terms; limited enrollment. Prerequisites: Ph 6 or APh 24, and Ph 7.* A one-term course in which students undertake a series of laboratory experi-

ments in atomic and laser physics. Topics include tunable diode lasers, saturated-absorption spectroscopy, Fabry-Perot cavities, laser frequency modulation, resonant atomic index-of-refraction, and laser frequency stabilization. Instructors: DeRose, Libbrecht.

Ph 77 ab. Advanced Physics Laboratory. *9 units; first, second, third terms. Prerequisites: Ph 6 and Ph 7.* A two-term laboratory course open to junior and senior physics majors to familiarize students with equipment and procedures used in the research laboratory. Experiments illustrate fundamental physical phenomena in atomic, low-temperature, nuclear, and particle physics, such as NMR, critical fields in superconductors, positron annihilation, and muon lifetime. Instructors: DeRose, 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 (Frautschi). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Laboratory work is required for this course. Two fifteen-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 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 (Frautschi). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Two fifteen-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 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. Instructors: Goldreich, Stevenson.

Ph 103 abc. Topics in Contemporary Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: permission of the instructor.* A series of introductory one-term, independent courses. Students may register for any particular term or terms.

a. Low Noise Electronic Measurement. *First term.* An introduction to ultralow noise electrical measurements, both DC and AC, as applied to experimental research. Topics include physical noise processes, signal transduction, models of small signal amplification, as well as modulation, detection, synchronous and lock-in detection, signal sampling techniques, digitization, signal transforms and correlations. Current approaches providing state-of-the-art sensitivity will be reviewed; topics may include DC SQUIDS, single electron transistors, transition-edge sensors, tunnel junction detectors, and various micro- and nanomechanical detectors. Instructor: Roukes.

b. 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 c. Neuroscience for Physicists and Engineers. *Third 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. Enrollment limited to 15, with preference given to physics seniors. Instructor: Pine.

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or their 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: Skelton, Zmuidzinas.

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. Instructor: Harrison.

Ph 118 ab. Electronic Circuits and Their Application to Physical Research. *9 units (3-0-6); second, third terms. Prerequisite: Ph 105 or equivalent.* A lecture course on fundamentals of electronics with

emphasis on proven techniques of instrumentation for scientific research. Both the physical principles and properties of electronic components and circuits, with emphasis on analog systems. Common electronic instruments, computer interfaces, and typical control logic in scientific research used as examples. Instructor: Drever. Typically given in alternate years; not offered 2000–2001.

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 their 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: Mabuchi.

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. If given as a three-quarter sequence, the third term will include a selection from more advanced topics such as renormalization group theory; strongly interacting quantum systems; applications to biological systems; and others. Instructor: Cross. In 2000–2001, offered as a two-term course in the second and third terms.

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 focuses on probability and statistics in physics. Third term covers group theoretic methods in physics. The three terms can be taken independently. In 2000–2001 only the first term and second terms will be offered. Instructors: Schwarz, Gottschalk.

Ph 130 abc. Condensed Matter Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 125 or Ph 125 or equivalent; statistical physics at level of APh 105 or Ph 127 also useful but not required.* The first two terms will provide an intensive focus upon fundamental concepts of condensed matter physics and their experimental underpinnings: simple models of the properties of solids; crystal lattices, symmetries, and binding; phonons, specific heat, and dispersion relations; electronic states in metals, semiconductors, and insulators; transport and scattering processes; basic principles of magnetism. Other topics introduced

may include disorder and localization; optical properties of solids; physics of surfaces, interfaces, and heterostructures; mesoscopic systems. Not offered 2000–2001.

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. Typically one term in each of three distinct areas. In 2000–2001, elementary particle physics, quantum optics, and nuclear physics will be offered first, second, and third terms, respectively. Terms may be taken separately. Instructors: Porter, Kimble, Hughes.

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. Instructors: Thorne, Blandford, Stevenson.

Ay/Ph 145. Signal Processing and Data Analysis. *9 units (3-0-6).* For course description, see Astronomy.

Ph 161 ab. Introduction to Complex Systems. *9 units (3-0-6); second, third terms. Prerequisites: Ph 136 or ACM 95/100 or Ph 129 provide a useful but not essential background.* An introduction to nonequilibrium physics, using systems from physics, fluid dynamics, chemistry, and biology as examples. The first term will study dissipative chaos. The emphasis of the second term will be the formation of spatial structures (sometimes called "dissipative structures" or "pattern formation"). Some familiarity with solutions to partial differential equations will be assumed, and computer assignments should be expected in the first term. Typically offered in alternate years. Instructor: Cross. Not offered 2000–2001.

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 or registration representative 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 or registration representative 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 or registration representative must be obtained before registering. Graded pass/fail.

CNS/Ph 175. Artificial Life. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/Bi/Ph 185. Collective Computation. *12 units (3-1-8).* 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.

Ph 203 abc. Nuclear Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or Ph 125 or equivalent.* Fundamental structure and properties of nuclei from the nucleon to nuclear matter. Topics will include electroweak and hadronic interactions in nuclear systems. Not offered every year.

Ph 205 abc. Relativistic Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or 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: Wise.

Ph 209 abc. Classical Electromagnetism. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106.* Electromagnetic fields in vacuum and in matter; boundary-value problems and Green's functions; retarded potentials; wave propagation; wave-guides and cavities; radiation, dispersion, and absorption; and special relativity. Instructor: Peck.

Ay/Ph 212. Topics in Astronomy: Cosmology and Particle Structure. *9 units (3-0-6).* For course description, see Astronomy.

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, effecient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructor: Preskill. For further information, see http://www.theory.caltech.edu/~preskill/ph219/.

Ph 220 ab. Special Topics in Condensed Matter Physics. *9 units (3-0-6); first and second terms. Prerequisites: Ph 127 and Ph 135 or equivalents, plus a basic knowledge of quantum field theory and simple renormalization group analysis, or permission of the instructor.* This course will cover special topics of central importance in modern condensed matter physics. The topics for the first term will include Fermi-liquid theory, non-Fermi liquids, Luttinger liquids, integer and fractional quantum Hall effects, and topological defects in guage-field theories. Second term, emphasis will be on special topics in superconductivity and superfluidity, including high-temperature superconductivity, heavy-Fermion superconductivity, and dual description of the superconductor-to-normal metal/superfluid-to-normal fluid transitions in three dimensions. Instructors: Sudbo, Yeh.

Ph/Ay 221 abc. Cosmology and Particle Astrophysics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 and Ph 125, or equivalents.* An introduction to current research in cosmology and particle astrophysics. First quarter will focus on basics of the Friedman-Robertson-Walker metric, aspects of physical cosmology, and gravitational lensing. Second quarter will include the early universe and particle astrophysics (e.g., inflation, phase transitions, neutrino astrophysics, particle dark matter, and baryogenesis). Third quarter will focus on cosmological perturbation theory, structure formation, and the cosmic microwave background. Instructor: Kamionkowski.

Ph/APh 223 abc. Advanced Topics in Condensed Matter Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 130 or equivalent, or permission of the instructor.* Content includes advanced topics in theoretical and experimental condensed matter physics, emphasizing the application of formal methods such as quantum field theory and group theory to diverse experimental phenomena in both the solid and liquid state. Topics to be covered include second quantization and many-body techniques; group theory and its application to electronic band structures, phonon spectroscopy and optical properties of metals and semiconductors; microscopic and phenomenological theories of superconductivity; and magnetism. Not offered 2000-2001.

Ph 224 abc. Space Physics and Astronomy. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 125, Ph 106, or equivalent.* Instrumental and observational aspects of space physics and astronomy, including high-energy astrophysics (X-ray, gamma-ray, and cosmic-ray astrophysics), and infrared/sub-mm space astronomy. Analysis of astronomical and technical aspects of current and future space physics and astronomy missions. Not offered 2000–2001.

Ph 225 ab. Quantum Optics. *9 units (3-0-6). Prerequisite: Ph 125 or Ph 125 or equivalent; the quantum optics term of Ph 135 or permission of the instructor.* An introduction to experimental and theoretical quantum optics with emphasis on modern topics related to quantum measurement and to dissipative quantum dynamics. The course will include

discussions of the classical and quantum theories of coherence, as well as of the interaction of the radiation field with simple atomic systems. Not offered 2000–2001.

Ph 228 ab. Topics in Mathematical Physics. *9 units (3-0-6). Prerequisite: instructor's permission.* Content changes from year to year. Not offered 2000–2001.

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. Instructor: Schwarz. In 2000–2001, only Ph 229 ab will be offered, during second and third terms.

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 nonabelian gauge field theories, including quark confinement, chiral symmetry breaking, anomalies, instantons, the 1/N expansion, lattice gauge theories, and topological solitons. Not offered 2000-2001.

Ph 231 abc. High-Energy Physics. *9 units (3-0-6); second, third terms. Prerequisite: Ph 125 or Ph 125 or equivalent.* An introduction to elementary particle physics, stressing experimental phenomenology, theoretical interpretations of this phenomenology, and experimental techniques. Classification of elementary particles using invariance principles, evidence for fundamental constituents, and examination of the experimental basis for currently interesting ideas, such as quantum chromodynamics, the "standard model" of weak and electromagnetic interactions, and supersymmetric and unified theories. Not offered 2000-2001.

Ph 234 abc. Topics in Theoretical Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 or equivalent.* The course covers the standard model for strong, weak, and electromagnetic interactions based on the gauge group SU(3) x SU(2) x U(1). Techniques such as the renormalization group and chiral perturbation theory will be used to make comparisons with experiments. Problems and extensions such as grand unification, low-energy supersymmetry, and axions will be discussed. Not offered 2000–2001.

Ph 235 ab. 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 2000–2001.

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, with emphasis on applications to astrophysical and cosmological problems. Instructor: Lindblom.

Ph 241. Research Conference in Physics. *No credit; first, second, third terms.* Meets weekly for a report and discussion of work appearing in the literature, and in progress at Caltech and elsewhere. Advanced students in physics and members of the physics staff take part.

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: Vogt.

Ph 250. Introduction to String Theory. *9 units (3-0-6); first, second, third terms. Prerequisites: 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 guage 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. Instructors: Witten, Gubser.

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.

PS 12. Introduction to Political Science. *9 units (3-0-6); second term.* 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. Instructor: Ordeshook.

PS 101. Selected Topics in Political Science. *Units to be determined by arrangement with the instructor. Offered by announcement.* Instructors: Staff.

PS 120. American Electoral Behavior and Party Strategy. *9 units (3-0-6).* 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.

PS 121. Congressional Policy Formation and Legislative Process. *9 units (3-0-6); second term.* Decision making in legislative bodies, with emphasis on the American Congress. An investigation into the impact of Congressional structure and practices on the policies adopted by the federal government. Instructor: Katz.

PS 122. Problems of Representation. *9 units (3-0-6). Prerequisite: PS 12.* Considers the theoretical foundations of democratic governments and modern problems of representation, including alternative approaches and solutions to representing minorities. Instructor: Staff. Not offered 2000–2001.

PS 123. Fiscal Federalism. *9 units (3-0-6); second term.* In the United States, as in many other countries, taxes are collected and benefits are provided by federal, state, and local governments. Because politicians like to take credit for benefits but avoid blame for taxes, fiscal relations between levels of government are an ongoing source of controversy and confusion. Course covers the major budgetary problems that currently face state, local, and federal governments. Specific topics will include intergovernmental revenue flows, the municipal bond market, and policy mandates. Grades only. Instructor: Kiewiet. Not offered 2000–2001.

PS/SS 125. Political Economy of Development. *9 units (3-0-6); third term. Prerequisite: PS 12 or SS 13.* The role of political institutions in economic development and the interplay between economic development and political change. The course applies tools drawn from economics and political science to examples from history and from current-day developing countries. Instructor: Hoffman.

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: Jackson.

PS/Ec 134. The Political Economy of Urban Areas. *9 units (3-0-6). Prerequisite: PS 12 or equivalent.* Development of a theory of urban government, using analytic concepts from microeconomics and political science. Instructor: Kiewiet. Not offered 2000–2001.

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. Instructor: Ordeshook. Not offered 2000–2001.

PS 141. A History of Budgetary Politics in the U.S. *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.

H/PS 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see History.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3).* For course description, see Economics.

PS/Ec 172. Noncooperative Games in Social Sciences. *9 units (3-0-6); first term. Prerequisites: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theory models in social science. Axiomatic utility theory and general noncooperative games. Instructor: McKelvey.

PS/Ec 173. Cooperation and Social Behavior. *9 units (3-0-6); first term. Prerequisite: PS/Ec 172 or consent of instructor.* Game theoretic and evolutionary approaches to modeling various types of cooperative, altruistic, and social behavior. Emphasis on economic and political applications. Instructor: Staff. Not offered 2000–2001.

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 incentives, social influence, liking, stereotyping, deception, fairness and altruism, and conformity. Instructor: Staff.

Psy 20. Introduction to Cognitive Psychology. *9 units (3-0-6); third 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 automaticy, 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: Camerer.

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 2000–2001.

Psy 101. Selected Topics in Psychology. *Units to be determined by arrangement with the instructor. Offered by announcement.* Instructors: Staff.

Psy 115. Cognitive Psychology. *9 units (3-0-6); third term. Prerequisite: Ma 112 or consent of instructor.* The study of how people think and behave. An introduction to the methods psychologists use to understand cognition, and the knowledge these methods have created: behaviorism (its rise and eclipse), memory, perception, learning, induction, categorization, intelligence, decision making and judgment, and evolutionary psychology. Instructor: Staff. Not offered 2000–2001.

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 130. Introduction to Human Memory. *9 units (3-0-6); third 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. Instructor: Staff. Not offered 2000–2001.

RUSSIAN *(see Languages)*

SCIENCE, ETHICS, AND SOCIETY/HISTORY AND PHILOSOPHY OF SCIENCE

Hum/H/SES 10 a. Introduction to the History of Science. *9 units (3-0-6). Offered by announcement.* For course description, see Humanities. Hum/H/SES 10 a may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement.

Hum/Pl/SES 10 b. Introduction to the Philosophy of Science. *9 units (3-0-6). Offered by announcement.* For course description, see Humanities. Hum/Pl/SES 10 b may be taken for credit toward the additional 36-unit HSS requirement by students who have already fulfilled their freshman humanities requirement.

SES 102 abc. Senior Seminar. *9 units (2-0-7).* The first two quarters consist of directed tutorial study and research to develop further the student's area of concentration in the option and to prepare the student for the writing of a research paper. Work in the tutorial will comprise intensive reading in the relevant literature and the beginnings of work on the paper. In the third quarter, students will present and discuss the results of their research and successive drafts of their papers in a seminar for discussion and criticism. Open to students in the SES option and the SES graduate minor, and to others by special permission. Instructors: Staff.

SES 103. Public Lecture Series. *1 unit (1-0-0).* Lectures offered under the rubric Science, Ethics, and Public Policy, featuring speakers from outside and inside Caltech, that introduce students to a broad variety of SES-related topics past and present. The seminar is held roughly four times per quarter. *Not available for credit toward humanities–social science requirement.* Instructors: Guest lecturers.

SES/Hum 121. Freud. *9 units (2-0-7).* The development of psychoanalysis, especially Freud's theories of hysteria and dreams, from its origins until the early years of the 20th century. Topics include the interplay between Freud's developing theories and clinical evidence and his relations with the scientific and medical community of the day. Instructor: Pigman.

SES/Pl 121. Foundations of Probability and Inductive Inference. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* Philosophical and conceptual issues arising from probability theory. Topics covered

may include the psychological literature on common fallacies in probabilistic reasoning; comparative probability; Kolmogorov's axiomatization of probability, and an exploration of both defences and criticisms thereof; the classical, analogical, logical, frequentist, propensity, and various subjectivist interpretations of probability; calibration; conditional probability as the primitive of probability theory; proposals for supplementing the probability calculus with certain further principles. Instructor: Hájek.

SES/Pl 122. Philosophy of Science. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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: Hajek.

SES/Pl 123. Causation and Explanation. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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. Instructors: Woodward, Hitchcock.

SES/Pl 125. Philosophy and Biology. *9 units (3-0-6). Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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. Instructor: Staff.

SES/Pl 126. Biomedical Ethics. *9 units (3-0-6). Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* Ethical and public policy issues arising from the biological sciences, biotechnology, and medical practice. Topics covered may include ethical and conceptual issues arising in the following areas: clinical decision making and patient autonomy, right to die and euthanasia, human genetics and genetic engineering, reproductive technology and abortion, health insurance and the allocation of medical resources. Instructors: Staff. Not offered 2000–2001.

SES/Pl 127. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7); third term. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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.

SES/H/Lit 128. British Science Fiction. *9 units (3-0-6).* This course will examine fictional representations of nature, scientific knowledge, and scientific method in 19th- and 20th-century Britain. Topics will include representations of the laboratory, the scientist, forensic science and detection, as well as imaginative reflections on future societies and other cultures and of the impact of the development of scientific culture and technological innovation on modern society. Sources will be drawn from novels, short stories, and films. They might include the work of H. G. Wells and Arthur C. Clarke, and specific sources like *The Island of Doctor Moreau, Brave New World, The Shape of Things to Come,* and *2001.* Instructor: Winter. Not offered 2000–2001.

SES/Pl 131. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6); first term. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* An introduction to the mind-body problem. The course surveys 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. Instructors: Cowie, Murphy.

SES/Pl 132. Philosophy and Biology. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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. Instructors: Cowie, Woodward, Quartz, Murphy.

SES/Pl 133. Philosophy of Physics. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* Philosophical and conceptual issues arising from physical theory. Topics covered may include the nature and existence of space and time, the relationship between mathematical models and physical reality, entropy and the direction of time, the nature of simultaneity, the possibility of time travel, determinism and indeterminism, and the interpretation of quantum measurement. Instructor: Hitchcock.

SES/Pl 135. Current Issues in Philosophical Psychology. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* 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 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, Murphy, Quartz.

SES/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. Instructor: Staff. Not offered 2000–2001.

SES/H 157. Science in America, 1865–Present. *9 units (3-0-6).* A study of the social and political history of American science, emphasizing the relationship of the research community to universities, industry, and government. Instructor: Kevles. Not offered 2000–2001.

SES/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. Instructor: J. Goodstein.

SES/H 159. Science and Society. *9 units (3-0-6); first term.* A historical examination from a socioeconomic, political, and ethical perspective of selected issues in science and technology — for example, biotechnology, human reproduction, nuclear power, and the environment. Instructor: Johns.

SES/H 160 ab. History of the Modern Physical Sciences. *9 units (3-0-6); second, third terms.* An exploration of the most significant scientific developments in the physical sciences from the late 19th century to the present. The first part of the course examines the emergence of new theories of radiation, the structure of matter, relativity, and quantum theory. The second part examines quantum mechanics, the devel-

opments in nuclear physics, atomic weapons, particle physics, and the organization of modern science. Scientific, historical, and philosophical texts will be used. (The two courses may be offered in alternate years.) Instructors: Barkan, Vogt.

SES/H 162. Social Studies of Science. *9 units (3-0-6).* 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. Instructors: Barkan, de Laet.

SES/H 163. Gender in the History of Science, Technology, and Medicine. *9 units (3-0-6); first term.* An examination of how notions of masculinity and femininity have influenced the history of science, technology, and medicine since 1600. Topics will include study of the rise of women in scientific and medical institutions and of the ongoing debates about whether men and women have (or have had) different ways of understanding the natural world. Instructor: Winter.

SES/H 164. Sciences of Mind and Society from the French Revolution to the Great War. *9 units (3-0-6).* The history of psychology, psychiatry, and social theory, beginning with the new definitions of madness, mental functioning, and social relations in the era of the French Revolution and ending with the emergence of 20th-century psychiatry after World War I. Instructors: Winter, Norris.

SES/H 165. History of Technology in the United States. *9 units (3-0-6).* An examination of technological innovation from 19th-century craft and mechanical technologies through the science-based varieties of the 20th century. Attention will also be given to the rise of the industrial research laboratory, technology in American life and culture, and the relationship of technological development to the activities of government, particularly the military. Instructors: Staff. Not offered 2000–2001.

SES/H 166. The History of Environmentalism. *9 units (3-0-6).* An examination of attitudes and ideas toward nature in American culture since the early 19th century and of the development of the environmental movement in the United States, including its recent globalization. Emphasis will be given to issues of preservation and conservation, pollution and public health, and conflicts of race, class, and economic interest in environmental policies and practices. Instructor: Staff.

SES/H 168. The History of Modern Medicine. *9 units (3-0-6); first term.* An examination of various themes in the history of medicine in western Europe and America since the Renaissance. Topics will include key developments of medical theory (such as the circulation of

the blood and germ theory), relations between doctors and patients, rivalries between different kinds of healers and therapists, and the development of the hospital and of laboratory medicine. Instructor: Winter.

SES/H 169. Selected Topics in Science, Ethics, and Society. *9 units (3-0-6). Offered by announcement.* Instructors: Staff, visiting lecturers.

SES/Pl 169. Selected Topics in Science, Ethics, and Society. *9 units (3-0-6). Offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* Instructors: Staff, visiting lecturers.

SES/Pl 185. Moral Philosophy. *9 units (3-0-6). Prerequisite: Hum/Pl 8 or Hum/Pl 9 or Hum/Pl/SES 10 b or permission of instructor.* A survey of topics in moral philosophy. The emphasis will be on meta-ethical issues, although some normative questions may be addressed. Meta-ethical 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. non-cognitivism, 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. Instructor: Staff.

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. Instructor: Davis.

EC/SS 20. Oral Presentation. *3 units (2-0-1).* For course description, see Economics.

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.

PS/SS 125. Political Economy of Development. *9 units (3-0-6).* For course description, see Political Science.

Ec/SS 128. Economic and Financial Development in the 19th and 20th Centuries. *9 units (3-0-6).* For course description, see Economics.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6).* For course description, see Economics.

Ec/SS 130. Economic History of Europe from the Middle Ages to the 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.

H/SS 154 ab. Race Relations in History and Social Science. *9 units (3-0-6).* For course description, see History.

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).* 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: Ghirardato, Palfrey, McKelvey.

SS 202 abc. Political Theory. *9 units (3-0-6).* 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: Banks, Ordeshook, Alvarez.

SS 203. American Electoral Processes. *9 units (3-0-6).* An in-depth analysis of American electoral processes, with emphasis on the application of new theory and quantitative techniques. Instructor: Kousser. Not offered 2000–2001.

SS 205 abc. Foundations of Economics. *9 units (3-0-6). Prerequisite: Ec 121 ab or consent of instructor.* 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, Jackson, Wilkie.

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: Banks, McKelvey.

SS 211 abc. Advanced Economic Theory. *9 units (3-0-6). 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: Ghirardato, Border.

SS 212 abc. 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. Instructors: Jackson, Palfrey, Camerer.

SS 213 abc. Financial Economics. *9 units (3-0-6).* First term: introduction to theoretical financial economics at the graduate level. Course covers leading financial models such as the capital asset pricing model and arbitrage pricing theory in depth. Second term: theory of asset pricing in a dynamic context. Considers both the discrete and continuous time cases. Third term: theory and tests of asset pricing (including option pricing and term structure). Theory and tests of market microstructure. Theory of international finance. Instructor: Bossaerts.

SS 215. Legal Aspects of the Economics and Politics of Regulation. *9 units (3-0-6).* Relationship between law and governmental regulation of economic enterprise. Instructor: Staff. Not offered 2000–2001.

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: Staff.

SS 222 abc. Econometrics. *9 units (3-0-6).* Introduction to the use of multivariate and nonlinear methods in the social sciences. Instructors: Sherman, Grether, Dubin.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6). 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, Grether.

SS 227 abc. Statistical Computing for Research in the Social Sciences. *9 units (3-0-6); first, second, third terms. Prerequisite: Consent of instructor.* Computational issues in the management and analysis of large databases for social scientific research. Maximum likelihood, nonlinear optimization, data reduction, time-series, and Markov chain Monte Carlo estimation. Integration of programming, numerical optimization, and statistical methodology. Survey of software for data analysis and presentation. Instructor: Staff.

SS 229 abc. Theoretical and Quantitative Dimensions of Historical Development. *9 units (3-0-6). 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 grade at the end of the third term. Instructors: Davis, Fohlin, Hoffman.

SS 231 abc. American Politics. *9 units (3-0-6).* 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. Instructors: Kiewiet, Katz, Alvarez.

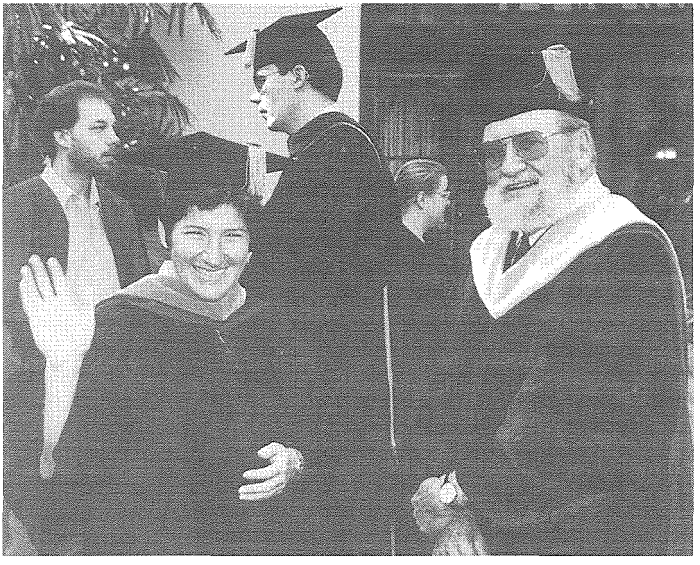
SS 232 abc. Historical and Comparative Perspectives in Political Analysis. *9 units (3-0-6). Prerequisite: SS 203.* Provides a knowledge and understanding of developments in both the American past and in other parts of the world. Instructor: Ordeshook.

SS 240. Techniques of Policy Research. *9 units (3-0-6). Prerequisites: SS 205 ab.* The application of social science theory and methods to the formulation and evaluation of public policy. Instructor: Dubin.

SS 260. Experimental Methods of Political Economy. *9 units (3-0-6).* 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. Instructor: Plott.

SS 300. Research in Social Science. *Variable units.* Instructor: Staff.

Trustees, Administration, Faculty



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Department of Physics
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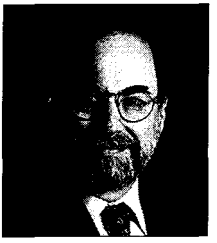

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Institute Administrative Council (IAC)—D. Baltimore, *Chair*; K.C. Border, C.E. Brennen, H.P. Daily, D.L. Goodstein, A.G. Horvath, W.A. Jenkins, S.E. Koonin, J.O. Ledyard, E.M. Meyerowitz, R.M. Murray, J.E. Nunnally, R.L. O'Rourke, T.W. Schmitt, J.H. Seinfeld, E.M. Stolper, E.C. Stone (Alternate: L.N. Dumas), D.A. Tirrell, T.A. Tombrello, M.L. Webster, H.M. Yohalem

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** indicates ex officio members*

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Vice Chair:	P.H. Patterson
Secretary:	W. Whaling

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Term expires June 30, 2001
P.L. Bossaerts
D.S. Burnett
F. Cowie
E.S. Phinney
J.P. Preskill
E.M. Schuman

Term expires June 30, 2002
F.H. Arnold
J.L. Beauchamp
M.R. Hoffmann
A.J. Rosakis
D.B. Wales
A. Winter

Term expires June 30, 2003
P. Bjorkman
W.F. Deverell
D.A. Dougherty
F. Raichlen
K.E. Sieh
S.R. Wiggins[1]

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Term expires June 30, 2002
D.L. Barkan, J.E. Bercaw, D.S. Cohen

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Term expires June 30, 2001
Ch., J.F. Brady, N.R. Corngold

Term expires June 30, 2002
T. Ahrens

Term expires June 30, 2003
S.J. Wilkie

Athletics and Physical Education

Term expires June 30, 2001
M. Bronner-Fraser

Term expires June 30, 2002
Ch., M.R. Hoffmann, J.B. Saleeby

Term expires June 30, 2003
H.B. Gray, R.H. Grubbs, A.P. Ingersoll

T. Downes*, H.D. Politzer*

Convocations

Term expires June 30, 2001
Ch., G.A. Lorden

Term expires June 30, 2002
A. Winter

Term expires June 30, 2003
C. Koch, C. Weinstein

D.R. Kiewiet*, J-P. Revel*

* *ex officio*

[1] *Leave of absence*

Core Curriculum Steering Committee
Term expires June 30, 2001
Ch., A.E. Lange, D.R. Kiewiet

Term expires June 30, 2002
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Term expires June 30, 2003
J.L. Kirschvink, N.S. Lewis, D.I. Meiron

Curriculum
Term expires June 30, 2001
Ch., H.B. Newman, J.M. Eiler, P. Ghirardato

Term expires June 30, 2002
K. Bhattacharya, R.P. Sherman

Term expires June 30, 2003
W.C. Brown, M. Ortiz, R.M. Wilson, K. Zinn

J.R. Goodstein*, J-P. Revel*

Educational Outreach
Term expires June 30, 2001
J.F. Brady, J.G. Hering

Term expires June 30, 2002
Ch., J. Pine, W.A. Goddard

Term expires June 30, 2003
R.A. Cameron, A. Winter

Foreign Students & Scholars
Term expires June 30, 2001
H. Engelhardt

Term expires June 30, 2002
Ch., E. Üstündag, D.C. Lis

Term expires June 30, 2003
A. King, H.A. Lester

P. Kia*

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Term expires June 30, 2002
Ch., D.M. Grether, R.D. Blandford, F.E.C. Culick, M.L. Hunt, N.J. Leonard, J.D. Roberts,

Term expires June 30, 2003
J.M. Allman, J.L. Beauchamp, A. Givental, A. Leonard, M.B. Wise

C. Liebau*

Graduate Study
Ch., P.W. Sternberg, Option Representatives

D.R. Kiewiet*

Health
Term expires June 30, 2001
Ch., P.T. Hoffman, P.O. Wennberg

Term expires June 30, 2002

Term expires June 30, 2003
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S.C. Frautschi*, D. Levy*, S.C. Miller*

Institute Programs
Term expires June 30, 2001
N.W. Tschoegl

Term expires June 30, 2002
Ch., J.G. Cohen, J. Pine

Term expires June 30, 2003
F.E.C. Culick, H.B. Keller, J.J. Morgan

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Library
Term expires June 30, 2001
Ch., K.M. Gilmartin, D. Gabai, G.R. Gavalas

Term expires June 30, 2002
G.W. Pigman

Term expires June 30, 2003
R.C. Flagan, C.W. Peck, G.R. Rossman

A. Buck*

Matriculation
Term expires June 30, 2001
K.C. Border, M. Feldblum, J.J. Hickey, D.K. Newman, N. Yeh

Term expires June 30, 2002

Term expires June 30, 2003
Ch., G. Ravichandran, T.D. Downes, A. Hajek, C. Jurca

Membership and Bylaws
Term expires June 30, 2001

Term expires June 30, 2002

Term expires June 30, 2003
H.F. Hall, Y.T. Hou, A. Kuppermann, J. La Belle, A.J. Rosakis

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Nominating Committee
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Patents & Relations With Industry
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Ch., Y-C. Tai, S.E. Fraser, W.G. Knauss

Term expires June 30, 2002
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Term expires June 30, 2003
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Term expires June 30, 2001
K.C. Border, S.C. Frautschi

Term expires June 30, 2002
Ch.,P.M. Bellan, C. Jurca, A. Kuppermann

Term expires June 30, 2003
C.M. Fohlin, A. Johns

D.M. Grether*, D. Levy*

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Term expires June 30, 2001
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J.L. Kirschvink, J. Zmuidzinas

Term expires June 30, 2003
Ch., C. Jurca, T.D. Downs, J.M. Stock

S.C. Frautschi*

Undergraduate Academic Standards & Honors
Term expires June 30, 2001
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Term expires June 30, 2002
J.G. Hering

Term expires June 30, 2003
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Upperclass Admissions
Term expires June 30, 2001
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Term expires June 30, 2002
Ch., J.Z. Lee, R.M. Wilson

Term expires June 30, 2003
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C. Liebau*

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TBA, *Executive Officer*

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[1] *Joint appointment with Carnegie Institution of Washington*

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Biology
Kai Zinn, Ph.D.
Biology

[1] *Joint appointment with Howard Hughes Medical Institute*
[2] *Undergraduate Student Adviser*

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Biology
Gilles J. Laurent, Ph.D., D.V.M.
Biology and Computational and Neural Systems
Stephen L. Mayo, Ph.D.[1]
Biology
Erin M. Schuman, Ph.D.[1]
Biology

[1] *Joint appointment with Howard Hughes Medical Institute*

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Biology

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Biology
Thomas J. Meade, Ph.D.
Biology
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Biology
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Biology

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Svenja Marianne Viete, Ph.D.
Doris Wagner, Ph.D.
John D. Wagner, Ph.D.
Jeong Kyo Yoon, Ph.D.
Chiou-Hwa Yuh, Ph.D.[1]

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Eric Mjolsness, Ph.D.

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Heinz Schuster, Ph.D.

Visiting Associates

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Peng-Sheng Chen, M.D.
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Clemens A. Neusch, M.D.
Jose L. Pena, M.D.
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Kathleen M. Sakamoto, Ph.D.
Neil Segil, Ph.D.
Mark A. J. Selleck, Ph.D.
Linda Ann Silveria, Ph.D.
Julian Michael Tyszka, Ph.D.
Leslie P. Weiner, M.D.
John C. Wood, M.D., Ph.D.

[1] *Joint appointment with Stowers Institute*
[2] *Joint appointment with Howard Hughes Medical Institute*

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Jerry E. Soloman, Ph.D.

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Ben Murray, Ph.D.
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Shirley Pease, B.Sc.
Piotr J. Polaczek, Ph.D.
Andrew J. Ransick, Ph.D.
Hiroaki Shizuya, M.D., Ph.D.
Bea (Natalie) Trifunac, Ph.D.

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Alexander Grunewald, Ph.D.
Leslie Kay, Ph.D.
Teresa A. Nick, Ph.D.
Krishna V. Shenoy, Ph.D.

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Michele Anderson, Ph.D.[2]
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Jordi Asin Cayuela, Ph.D.
Meyer Barebaum, Ph.D.
Imre Barta, Ph.D.
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Melanie Jean Bennett, Ph.D.
Alexandrine Bilwes, Ph.D.
Axel Blau, Ph.D.
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Jyl K. Boline, Ph.D.
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Boris Breznen, Ph.D.
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Ian Edward Brown, Ph.D.
Ted J. Brummel, Ph.D.
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John Burr, Ph.D.
Cristina Calestani, Ph.D.
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Ching-Kang Chen, Ph.D.
Chi-Sung Chiu, Ph.D.
Sangdun Choi, Ph.D.
Jeroen Corver, Ph.D.
Hong Dang, Ph.D.
Wei Dang, Ph.D.
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[1] *Joint appointment with Howard Hughes Medical Institute*
[2] *Joint appointment with Stowers Institute*

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