Caltech

Catalog

1990-91

CALTECH CATALOG 1990–91

California Institute of Technology
Pasadena, California 91125
(818) 356-6811

September 1990

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Trustees, Administration, Faculty

ACADEMIC CALENDAR 1990–91

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New Student Orientation for Graduates

September 26–28
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General Registration for undergraduates—8:30 a.m.–3:30 p.m.
Undergraduate Academic Standards and Honors Committee—9:00 a.m.

October 8
Last day for undergraduates to register for first term, 1990–91

October 19
Last day for adding courses and removing conditions and incompletes

October 31–November 6
Midterm examination period

November 12
Midterm deficiency notices due—9:00 a.m.
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November 21
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November 22–25
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*First due date for final examinations

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

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Last day for undergraduates to register for second term, 1990–91

January 25
Last day for adding courses and removing conditions and incompletes

February 6–12
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February 25–March 8
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*First due date for final examinations

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June 12–14*
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June 21
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July 4
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September 2
Labor Day holiday

FIRST TERM 1991–1992

September 25
Registration of new students: graduate students—8:30 a.m.–noon; undergraduates—1:00–4:00 p.m.
New Student Orientation for Graduates

September 26–28
New Student Orientation for Undergraduates

September 30
Beginning of instruction—8:00 a.m.
General Registration for undergraduates—8:30 a.m.–3:30 p.m.
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California Institute of Technology

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Section One

GENERAL INFORMATION

INTRODUCTION

The California Institute of Technology is an independent, privately supported institution officially classed as a university, and is accredited by the Accrediting Commission for Senior Colleges and Universities of the Western Association of Schools and Colleges. Caltech conducts instruction at both the undergraduate and graduate levels and, including its off-campus facilities, is also one of the world's major research centers. "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.

The primary purpose of the undergraduate school of the California Institute of Technology, as stated by the original trustees, is "to train the creative type of scientist or engineer so urgently needed in our educational, governmental, and industrial development." One factor in the Institute's attainment of this goal for both undergraduate and graduate students is undoubtedly the close contacts between a relatively small group of students (approximately 850 undergraduate and 1,000 graduate students) and the members of a relatively large research staff (approximately 800 faculty members).

In his inaugural address, Caltech president Thomas E. Everhart evaluated the nature and stature of the Institute as follows: "In 1988, when we hear concerns about economic competitiveness, when we are still recovering from the Challenger disaster, when our grade schools and high schools are not as competitive as we would like, when we cannot find the will to balance our national budget, 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."

Undergraduate Program

Caltech offers a four-year undergraduate course with options available in applied mathematics, applied physics, astronomy, biology, chemical engineering, chemistry, economics, electrical engineering, engineering and applied science, geochemistry, geology, geophysics, history, independent studies, literature, mathematics, physics, planetary science, and social science. Each leads to the degree of Bachelor of Science.

All options require students to take courses in 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 slightly over 50 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 Engineer's degree 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 mathematics, applied mechanics, applied physics, astronomy, biology, chemical engineering, chemistry, civil engineering, computation and neural systems, computer science, electrical engineering, engineering science, environmental engineering science, geological and planetary sciences, materials science, mathematics, mechanical engineering, physics, and social science.

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 cultural scientific training."

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 9 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 800 undergraduates, 1,000 graduate students, and 1,025 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.

This 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 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 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 to the California Institute of Technology, 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 unmanned space exploration. The Laboratory developed the first U.S. satellite, Explorer I, which was launched in 1958, and managed the Ranger, Surveyor, Mariner, Viking, and Voyager programs of lunar and planetary exploration for NASA, as well as the Galileo program now under way. The Infrared Astronomical Satellite (IRAS) has recently provided a wealth of data on the infrared sky. The Laboratory also operates the NASA worldwide deep-space tracking network and conducts a program of supporting research in space science and engineering.

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

In the fall of 1987, Dr. Thomas E. Everhart became president of Caltech, coming to the Institute from his position as chancellor at the University of Illinois at Urbana-Champaign. Prior to that he had been dean of Cornell University's College of Engineering. Dr. Everhart did his undergraduate work at Harvard, where he graduated magna cum laude with an A.B. in physics. He earned an M.Sc. in applied physics at UCLA and a Ph.D. in engineering at Cambridge University. He has gained international recognition for his work in the development of electron microscopy; he has also done research on electron beams as applied to the analysis and fabrication of semiconductors.

As Caltech has developed in effectiveness and in prestige, it has attracted a steady flow of gifts for buildings, for endowment, and for current operations. The gifts invested in plant now total $441,000,000 and those invested in endowment about $500,000,000. Very substantial grants and contracts from the federal government support many research activities.

Today Caltech has more than 16,000 alumni scattered 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
Leo James Rainwater, B.S. '39	physics	1975
Howard M. Temin, Ph.D. '60	physiology or medicine	1975
William 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

Caltech Crafoord Laureate

*Gerald J. Wasserburg, Ph.D. '54	geochemistry	1986

**In residence*

BUILDINGS AND FACILITIES

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.

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 chairman 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 member and director of The Caltech Associates.

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 chairman, 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 chairman, 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 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.

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

Mosher-Jorgensen House. The gift of Mr. Samuel B. Mosher of Los Angeles and Mr. Earle M. Jorgensen of Los Angeles. Mr. Jorgensen is a member of the Board of Trustees.

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 Caltech Y.

Willis H. Booth Computing Center, 1963. Built with funds given by the Booth-Ferris Foundation of New York and the National Science Foundation. Named in memory of Mr. Willis H. Booth, a member of The Caltech Associates.

Beckman Auditorium, 1964. The gift of Dr. and Mrs. Arnold O. Beckman of Corona del Mar. Dr. Beckman, an alumnus, was a member of the Institute's faculty from 1928 to 1939, a member of the Board of Trustees since 1953, chairman of the Board from 1964 to 1974, and is now chairman 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 chairman 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 Arthur Amos Noyes, director of the Gates and Crellin Laboratories of Chemistry and chairman 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 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 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 is a member of the Board of Trustees.

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 chairman emeritus of the Board of Trustees.

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

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

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

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. John G Braun is a member of the 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.

Infrared Processing and Analysis Center, 1986.

Beckman Institute, 1989. Built with funds provided by the Arnold and Mabel Beckman Foundation and other private donors.

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 Rockefeller sources.

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.

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

W. M. Keck Observatory, Mauna Kea, Hawaii. Built with funds provided by the W. M. Keck Foundation. Under construction.

Libraries

The Caltech library system is organized into 16 departmental or subject libraries; six are in the Millikan Library and ten are distributed throughout the campus. The libraries collectively subscribe to 6,370 journals, contain 455,500 volumes, and have extensive collections of microfilm, government documents, archives, and maps.

The Robert A. Millikan Memorial Library includes the collections of biology, chemistry, mathematics, physics, engineering, and humanities and social sciences. The circulation and reserve operations are on the first floor; the microfilm and government documents collections are on the fifth floor, and the photocopy service is in the basement. The Millikan Library is open weekdays during the school year from 8 a.m. to 1 a.m., and weekends from 9 a.m. until midnight.

The library collections located elsewhere on campus include aeronautics, applied physics and electrical engineering, archives and rare books, astrophysics, chemical engineering, computer science, earthquake engineering, environmental engineering, geology, management, and public affairs. The Library online public access catalog includes the records of books and journals held by the Caltech Libraries. Also available online are the recent citations to articles in approximately 2,000 science and technology journals to which the library subscribes. Special services that are available through the Caltech libraries include computerized literature searches, document delivery, interlibrary loans, and intercampus transportation between the Caltech, UCLA, and USC libraries.

Beckman Institute

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

Campus Computing Organization

The Campus Computing Organization (CCO) was created in 1986 to address the dynamic and complex computing support needs of the distributed computing environment at the Institute. The CCO provides comprehensive support for the hundreds of personal computers in use on the campus. This includes system selection assistance, procurement, installation, maintenance, repair, consulting, and supplies.

The CCO provides resources to support educational computing. These include obtaining appropriate hardware and software and a large number of personal computers for student use, and assisting in the development of effective use of computers in the educational processes. Minicomputers and workstations, including a VAX/VMS cluster with three VAX 11/750s and one VAX 8350, are also available for student use.

The CCO manages and maintains CITnet, Caltech's campus-wide local area network. This activity includes the support of connections to local, regional, national, and international networks, the development of shared network resources, and the maintenance of a campus electronic mail system.

The Computing Information Center, located in the Jorgensen building, provides a documentation library, a VAX software library, and four general-use microcomputer labs with computers from IBM, APPLE, SUN, and NeXT. A periodical entitled *Caltech Computing Newsletter* is published by the CCO, and is available free of charge by calling extension 4612.

Industrial Relations Center

The Industrial Relations Center develops and offers programs on linking emerging technologies with management strategies and practices, improving the effectiveness of manufacturing 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, 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 S. Hill Avenue. The latest calendar of programs or more information may be obtained by calling extension 4041.

POSTDOCTORAL APPOINTMENTS

Each year Caltech appoints a number of postdoctoral research fellows for definite terms, usually one year. The postdoctoral program generally consists of fundamental research in one of the Caltech laboratories in close association with one or more regular faculty members. Caltech is an affirmative action employer. All interested persons are encouraged to apply.

SHERMAN FAIRCHILD DISTINGUISHED SCHOLARS PROGRAM

The Sherman Fairchild Distinguished Scholars Program brings renowned scientists and scholars to Caltech. Through this program, Caltech's faculty and student body have an opportunity to be influenced in both teaching and research by the wisdom and experience of eminent world leaders in various fields. The emphasis in the program is on giving faculty and students exposure to Fairchild Scholars in all academic divisions—through discussions, seminars, lectures, and research—and establishing a forum for the exchange of ideas among Fairchild Scholars, Caltech faculty and students, and industry. Appointments are usually from three to nine months during the academic year.

UNDERGRADUATE RESEARCH

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 research sponsor, 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 sponsors. Proposals and recommendations are reviewed and awards granted by the members of the SURF administrative committee. The work is carried out during a ten-week period in the summer. Students may attend weekly seminars presented by members of the Caltech faculty and JPL technical staff each Wednesday of the program and may participate in luncheon roundtable discussions with leaders in business, government, or academia. Frequently discussion leaders are Caltech alumni. 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 1990, SURF students were paid $3,000. Applications are available in January and are due in early March. Awards are announced in mid-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 UASH reinstatement meeting and must not be on medical leave or under disciplinary sanction. For further information regarding this program, call the SURF Office, Room 3 Dabney, (818) 356-3675.

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 a member of the faculty known as the Master of Student Houses, as well as an Associate Master who shares the responsibilities for counseling students.

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 houses except on weekends. Students living in student houses should use their house name and mail code, California Institute of Technology, Pasadena, CA 91126, to facilitate handling of mail at the campus post office.

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 Baby Furniture Pool and 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, ASCIT copy card sales, 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 is 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 Southern California Inter-Collegiate Athletic Conference, intercollegiate competition is carried on in 11 sports with such schools as Claremont-Harvey Mudd, La Verne, Occidental, Pomona-Pitzer, Redlands, and Whittier. Athletes who distinguish themselves locally are able to compete at regional and national levels.

The athletic facilities include a football field, a standard running track, a soccer field, baseball and softball diamonds, and eight tennis courts. The Scott Brown Gymnasium provides facilities for badminton, basketball, and volleyball, and is adjoined by two modern swimming pools. A well-equipped weight room completes the on-campus athletic facilities. In addition, Caltech owns six Flying Junior sailboats that serve both instructional and competitive interests.

The Institute sponsors a vigorous program of intramural competition in nine sports. The Interhouse Trophy is awarded annually to the house accumulating the most points in this competition. The Varsity Rating Trophy is awarded to the house having the greatest participation in intercollegiate sports. A third trophy, Discobolus, is a bronze replica of Myron's famous statue of the discus thrower. A challenge trophy, awarded for competition in any sport, it remains in the possession of a house only so long as that house can defeat the challengers.

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 Caltech Alpine Club.

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 Council performs essentially the same functions for the graduate students that the Board of Directors of ASCIT does for the undergraduates.

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 in 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 Winnett Student Center. It is equipped by the Institute, largely through donations, and is operated by the students.

Here qualified students may work on private projects that require tools and equipment not otherwise available. All students are eligible to apply for membership in the Student Shop; applications are acted on by a governing committee of students. Members not proficient in power tools are limited to hand tools and bench work; however, instruction in power tools is given as needed. Yearly dues are collected to provide for maintenance and replacement.

The Caltech Y
The Y is located on the upper floor of the Winnett Student Center. 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 ski trips and backpacking adventures, subsidizes theater and sports tickets, administers the annual $2,000 Studenski travel award, has a 24-hour Xerox machine and a stereophonic lounge, provides free weekly outdoor campus concerts, runs a used-textbook exchange and the lost and found, offers personal counseling, rents camping equipment, sponsors guest speakers of national fame or local significance, and coordinates the annual Ametek Leadership Institute. No membership lists; no fees; no catches.

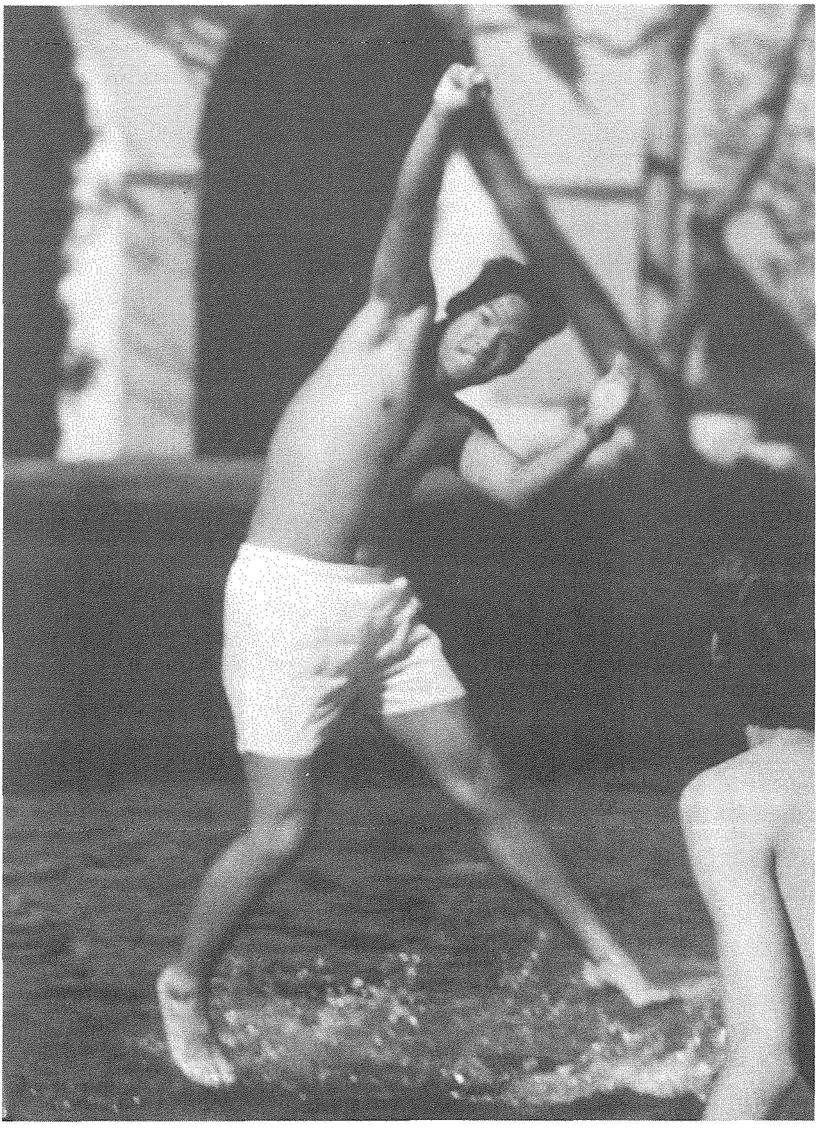
Human Relations Adviser
The Human Relations Adviser provides informal assistance in resolving intracampus conflicts, disputes, and grievances and promotes fair and equitable treatment within the Institute. Any member of the Caltech community (students, faculty, and staff) may receive confidential and independent assistance from the Human Relations Office.

Religious Life
In addition to several groups active on campus such as the Caltech Christian Fellowship, the Newman Club, and Hillel, churches 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. The auditoriums also serve as the stage for the annual Caltech Musical and the Caltech Glee Clubs' annual Home Concert. Tickets, often with discounts available, are offered to Caltech students for all events in Beckman and Ramo auditoriums. Located in the Office of Public Events are a ticket agency (handling tickets not only for Caltech events, but also for most southern California entertainment, sports, and cultural events) and the campus Audio-Visual Services Unit (where projectors, tape recorders, and video equipment may be obtained).

Bookstore

The student store serves students, faculty, and staff, and is located on the ground floor of the Winnett Student Center. Owned and operated by the Institute, the store carries a complete stock of required books and supplies, reference books, greeting cards, sweatshirts, and sundries as well as an extensive collection of paperbacks and other books of general interest.



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, which includes a dispensary and an infirmary, provides for undergraduate and graduate students the following services: (1) office consultation and treatment by a staff physician at prescribed hours; (2) laboratory tests, consultations, and radiographs as prescribed or ordered by the staff physician; (3) inoculations and treatments administered by nurse practitioners; (4) routine medications, prescription drugs, and other supplies at cost; and (5) infirmary care. Services are available for faculty and staff on a limited basis, covering only emergency care, on-the-job injuries, and inoculations.

Student Counseling Service
Individual, group, and crises treatment services are provided by a staff of Institute counselors and a consulting psychiatrist.

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 out-patient treatment for injury or illness. Benefits continue for 12 months, on and off campus, provided 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 DEVELOPMENT

Career Services
The Career Development Center provides assistance to students, research fellows, 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.

Campus Recruiting Program
Through the campus recruiting program, on-campus employment interviews are arranged with about 200 companies that seek full-time employees with B.S., M.S., or Ph.D. degrees. All graduating students, research fellows, and recent alumni are eligible to participate.

Career Day
Each February, between 35 and 40 different companies send representatives to campus for a day of informal discussion with students. Most bring informative displays and literature, and many of the representatives are Caltech alumni themselves.

Career and Employment Information Library
This resource library contains college and graduate school catalogues, scholarship and fellowship information, company literature, employer directories, career literature, audio-visual resources, and current employment opportunities.

Day on the Job
Students participating in the Day on the Job program have the opportunity to visit Caltech alumni on the job to discuss career options and to tour company facilities.

Part-Time Employment
Job listings (both on and off campus) are maintained in the Employment Information Library for students seeking part-time employment or work-study employment during the school year. Part-time employment provides students with the opportunity to help finance their education and to gain relevant work experience. (See also Student Employment, under Financial Aid in Section 3.)

A Summer Program in Research and Engineering (ASPIRE)
The ASPIRE program provides opportunities for students at all levels to participate in research and engineering projects in private industry, government laboratories, and other nonprofit agencies. Many positions are with

Caltech alumni. Students may see a career counselor to receive individual help in defining their summer work interests, résumé preparation, and job search strategies. A student database is used to match student interests and skills to positions related to both their career goals and geographic preferences. Application times for specific positions may be as early as December or as late as May. Besides paying a salary, many employers help students with transportation and summer housing. Students are encouraged to come in during the fall term to get on the database.

Annual Report
The office surveys all graduating students and compiles a detailed annual report that provides information on the plans of graduating students. Included are graduate schools attended, types of employers chosen, and salary statistics. (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.

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 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 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 will be used in computing the cumulative grade-point average.

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

The grade E indicates deficiencies that may be made up without repeating the course. The instructor giving the grade of E should state on the grade sheet the nature of the deficiencies and the time limit within which the work must be completed. At the end of this time period, the instructor should submit the appropriate letter grade, including P or F, and this will be placed on the student's record. After a student has been awarded the grade of E six or more 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 UASH in an exceptional case. Such a petition requires the support of the instructor and the Dean or Associate Dean of Students.

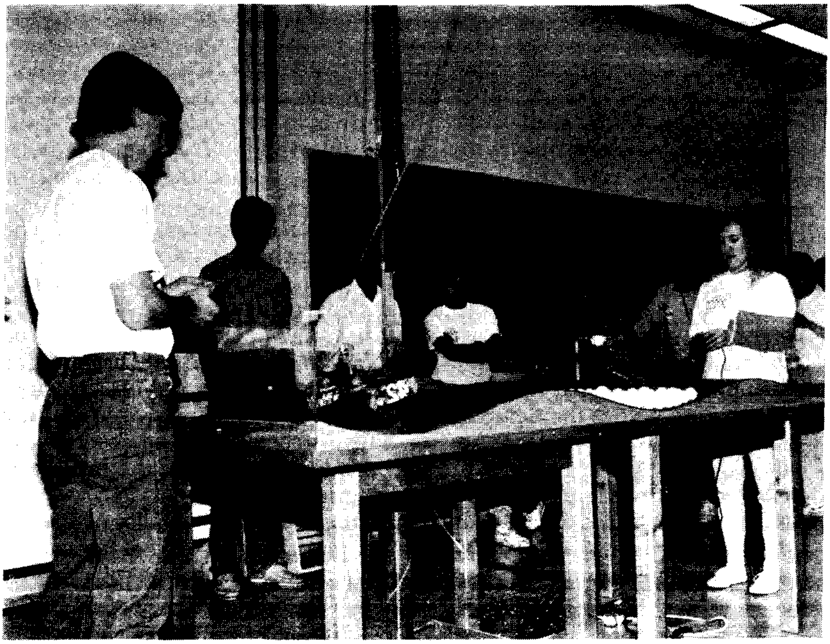
The grade I is given only in case of sickness or other emergency that justifies noncompletion of the work at the usual time, and its use must be approved by the Dean of Graduate Studies or the Dean of Undergraduate Students. Any grade I not so approved will be recorded as an E. As with the grade E, the time period within which the grade I is to be made up should be indicated on the grade sheet.

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:

- Freshmen receive pass/fail grades in all courses by virtue of their classification as freshmen by an admissions committee or, for students whose status after the first year is uncertain, by the Undergraduate Academic Standards and Honors Committee.
- All other students, undergraduate and graduate, in courses with numbers under 200 will receive letter grades unless the course is designated "graded pass/fail" or unless, when it is allowed, the student files with the 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 preregistration 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 preregistration.
- 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 81 may be in courses graded pass/fail because of the student's election.

NOTICES AND AGREEMENTS

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 Accreditation Board for Engineering and Technology has accredited our B.S. programs in chemical 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

The California Institute of Technology is committed to the concept of equal educational opportunity for all. Individuals are considered for admission to student status, and all services, facilities, programs, and activities are administered in a nondiscriminatory manner without regard to (a) race, religion, color, sex, national or ethnic origin or nondisqualifying handicap in accordance with existing laws and regulations, including Title IX of the Education Amendments of 1972, Title VI of the Civil Rights Act of 1964, and Section 504 of the Rehabilitation Act of 1973 as amended; or (b) any other factor which is, in fact, irrelevant to student status or to the rendering of services, facilities, programs, or activities.

The grievance procedure described below is the Institute's official avenue for redress of grievances of alleged discrimination. The Vice President for Student Affairs is the Institute official responsible for investigating student complaints of discrimination. Informal assistance and consultation about possible discrimination or about grievance procedures may be obtained from the Human Relations Adviser.

Harassment

The Institute attempts to maintain a climate of mutual respect among all members of the community. Harassment of any kind is inappropriate and strongly discouraged. Any member of the Caltech community who feels that he or she has been harassed should lodge a complaint promptly. An official policy statement regarding sexual harassment is available from the Dean of Students, the Dean of Graduate Studies, or the Vice President for Student Affairs. The Vice President for Student Affairs is the ombudsman for student grievances (see below). All members of the Caltech community may consult with their supervisors, the Human Relations Adviser, personnel in the Employee Assistance Program, or other individuals deemed appropriate, regarding harassment.

Student Grievance Procedure

Caltech provides a variety of routes, most of them informal, by which student complaints are brought to consideration and resolution. These routes normally depend on the nature of the complaint. In academic matters, for example, they begin with teacher-student conversations and extend to the Deans, the Division Chairmen, the Registrar, and various committees having faculty and student members. Undergraduate housing matters relate primarily to the house government organizations, and to the Resident Associates and the Master of Student Houses. The Dean of Graduate Studies often serves as ombudsman in graduate student matters. The Graduate Student Council and the Associated Students of Caltech may become responsibly involved in important complaints. Sometimes *ad hoc* groups are formed to consider and make recommendations in particular areas. The Human Relations Adviser, who acts as an ombudsman for the entire Caltech community, may be confidentially consulted about any problem not resolved by other offices.

The grievance procedure is intended to deal with complaints for which reasonable efforts by the available informal routes have not led to prompt and acceptable resolution, and which do not fall within the jurisdiction of the Honor System.

The first step in this procedure is to submit the matter to the Vice President for Student Affairs, who is the ombudsman for student grievances. He will work with the grievant in attempting to resolve the matter. If the grievant is dissatisfied with the results, the grievant may appeal the case to the Grievance Committee. This committee consists of two members of each of the categories—undergraduate students, graduate students, faculty, and administration—appointed, respectively, by the ASCIT Board of Directors, the Graduate Student Council, the Chairman of the Faculty, and the President of the Institute. The Chairman of the Committee, nonvoting except in the case of a tie, is also appointed by the President. 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 Vice President for Student Affairs, the Dean of Students, the Dean of Graduate Studies, or the Human Relations Adviser.

Employment Experience of Recent Graduates

A survey was made at the end of June 1989 of the future plans of those students who had graduated at the commencement ceremony on June 16, 1989.

Of those receiving the B.S. degree about whom we have definite information, 50% had been accepted for admission to graduate school for further education, 31% had accepted employment, 12% were uncommitted, and 7% had other plans. The average salary of those accepting employment was $2,750 per month. At the M.S. level, 64% were continuing in graduate school, 25% were employed at an average salary of $3,297 per month, 4% were uncommitted, and 7% had other plans. Of those receiving the Ph.D. degree, 2% were continuing in graduate school, 93% were employed at an average salary of $4,142 per month, 3% were uncommitted, and 2% had other plans.

Student Retention

Most undergraduates enter Caltech at the freshman level. Of those, over the last several years, 80% have graduated from the Institute with Bachelor of Science degrees in the options of their choice. Of students registering for the first time as sophomores or juniors, 92% have graduated. At the graduate level, 91% of entering students graduate either with the degree of Master of Science or of Doctor of Philosophy or, occasionally, with both.

Student Patent and Computer Software Agreement

Students at Caltech have many opportunities to work in laboratories or 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 which 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, non-exclusive 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 which is first conceived or first actually reduced to practice, or computer software first written, under the conditions of paragraphs 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 paragraphs 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 following constitutes the policy of the California Institute of Technology regarding access to student records:

1. The Institute maintains 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.
2. The Registrar of the Institute is responsible for maintaining all of these records, except for those involving Financial Aid. They are available

to the Registrar, to the Vice President for Student Affairs, to the Dean of Graduate Studies, to the Director of Financial Aid, to the 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 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. This record will indicate specifically the legitimate interest that each person or organization obtaining access to the records has in such records.

3. Students are allowed access to their 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 their deputies, as appropriate. A mutually convenient time will be arranged within ten 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 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 for the first page copied and $.12 for each additional page. All reasonable requests for explanations or interpretations of the records will be honored, and if inaccurate, misleading, or otherwise inappropriate data are found in the 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 their deputies, do not agree on any item contained in the 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 Chairman 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 record, as determined by majority vote, will be in writing, will be rendered within ten 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 records a statement commenting on the information in the records and/or setting forth any reasons for disagreeing with the decision of the Institute.

4. The Institute considers the following to be directory information: student's name, address, telephone listing, date and place of birth, major field of study, 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.
5. A student will not be required to waive any rights regarding access to student 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.
6. The Institute reserves the right to destroy from time to time any and all 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 a decision to deny such access has been arrived at as described in (3) of this section.
7. The Institute also maintains for each student a medical record showing history, treatment, etc. These records are maintained at the Young Health Center and are available for inspection by the individual student on request.

Academic Records of Veterans

The Institute maintains a written record of a student's previous education and training. 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 re-enrolls in that course and successfully completes it, that fact will be noted on his or her permanent record card. Since the Institute does not offer resident courses not leading to a standard college degree, no attendance records are maintained for such courses.

Section Two

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 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 re-entering 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 that 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 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 gas dynamics, diffraction of shock 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 volcanoes. 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. Computational fluid dynamics is a relatively new discipline in which 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, 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 the aerodynamics of automobiles and trucks, turbulent mixing in chemical lasers, turbulent combustion, laminar diffusion flames and their instabilities, fires in buildings (turbulent mixing and flow fields driven by fire-produced buoyancy), hydrodynamics and two-phase flows, and active and passive control of transition and turbulence.

Structural Mechanics. Structural mechanics research involves both the static and dynamic behavior of structures. Included are buckling for both the elastic and viscoelastic (composite) materials. Other subjects include the failure of composite materials and the behavior of large space structures.

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, and 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 structural 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 aero-acoustics are actively under study at GALCIT. They include jet noise, combustion noise, and nonlinear acoustics and hydro-acoustics. A particularly interesting problem is the generation of combustion-induced organ pipe oscillations in large burners of electric generating plants.

The Daniel and Florence Guggenheim Jet Propulsion Center conducts a large portion of its instruction and research in close cooperation with the aeronautics group. The fields of study covered are described under the separate heading of Jet Propulsion. Students in aeronautics are able to pursue studies and research leading to graduate degrees in aeronautics, utilizing facilities, courses, and research supervision by the faculty of the Jet Propulsion Center.

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, the GALCIT 10-ft. Wind Tunnel, and many 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. A new shock tunnel for studying hyper-velocity gas flows up to 7 km/s is scheduled for completion in the fall of 1990. Shock tubes, plasma tunnels, and other special facilities are available for the study of extreme temperatures, shock waves, acoustics, and cryogenic flow.

The solid mechanics laboratories contain standard as well as special testing machines for research related to aircraft and spacecraft structures and materials under static and dynamic loads, including three servohydraulic facilities, two of which operate in a "tension/torsion" mode. Specialized fatigue facilities and a variety of optical methods and relevant equipment are available, as well as other special apparatus, including laser equipment and a line of high-speed cameras offering recording at rates from still to 500,000 frames per second, for study of elastic waves, dynamic buckling, and the mechanics of static and dynamic fracture.

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.

A graphics workstation is available to support research in computational fluid dynamics. This workstation provides high resolution color graphics with a capability of viewing three-dimensional information at high speed, computing power of approximately 1-3 times a VAX 11/780, storage capability of 440 Megabytes, and an interface to the campus computer network and to ARPAnet so that programs and results can be sent to and from remote supercomputers.

APPLIED MATHEMATICS

An interdisciplinary program of study in applied 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 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 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 developing advanced computers. The applied mathematics group has access to super-computers 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 applied mathematics.

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 mathematics, and those that have a special applied 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, computational fluid dynamics, dynamical systems, and advanced elasticity. Through study outside of applied mathematics, each student is expected to become competent in some special physical or non-mathematical field. In this way, subjects for research appear naturally, and a broad educational program is provided.

The present group primarily interested in applied mathematics consists of approximately 25 students and nine professors. Also, each year many distinguished visitors either come 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, elasticity, dynamical systems, 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, 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 and fluid media, fluid mechanics, mechanics of quasi-static and dynamic fracture, structural mechanics and stability, dynamics and mechanical vibrations, finite element analysis, stability and control, and certain areas in the fields of propulsion, heat transfer, and generation of energy.

Research studies in these areas that illustrate current interests include linear and nonlinear vibrations, structural dynamics and design for earthquake and wind loads, linear and nonlinear problems in static and dynamic elasticity, plasticity, and viscoelasticity, wave propagation in elastic and viscoelastic media, 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 grown up 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. Another specialized laboratory is the heat transfer laboratory, which contains a forced convection heat transfer loop and facilities for studying the performance of high-speed pumps.

APPLIED PHYSICS

An interdivisional program in applied physics for both undergraduate and graduate study was initiated in 1970. Like applied mathematics, 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 similarly are admitted to 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 neutron 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 has been enriched recently by the construction of the 40,000-sq.-ft. 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 Big Bear, plus the Owens Valley Radio Observatory and the Caltech Submillimeter Observatory, together constitute a unique and unprecedented concentration of scientific facilities in astronomy. 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 white dwarfs and other stars near the end-point of evolution; studies of the dynamics and composition of galaxies and clusters, nebulae, and interstellar matter; statistical studies pertinent to the structure of the galaxy; 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, the physical properties of galactic and extragalactic radio sources, including quasars, 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 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. 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 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 electronic detectors, some of which are constructed in Robinson Laboratory.

A multipurpose solar equatorial telescope has been installed at an observing station at Big Bear Lake. 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 new effort is the study of solar oscillations.

Special apparatus for detection and measurement of radiation in the far infrared has been fitted to various telescopes for the study of planets, cool stars, and dust clouds, as well as quasars and the energetic nuclei of galaxies.

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-m parabolic antenna, a three-element millimeter-wave synthesis interferometer array, a two-element interferometer for solar studies, and a 5.5-m telescope dedicated to observations of the microwave background radiation. The 40-m telescope is used in conjunction with other radio telescopes around the world for very long baseline interferometry (VLBI), a technique that permits mapping of compact galactic and extragalactic objects with angular resolution better than one millisecond of arc. The 40-m is also used alone for continuum and spectroscopic studies of radio sources and of the microwave background radiation. The millimeter-wave array consists of three high-precision 10-m antennas and is used at wavelengths of 1.3 to 4 mm to map the distribution of interstellar gas and dust in our own and other galaxies and for studies of planetary atmospheres, stellar envelopes, and regions of star formation. 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.

A major new facility is under construction on Mauna Kea, in Hawaii. The Caltech 10-m submillimeter telescope was completed in 1986. The Keck 10-m optical telescope, which is to be operated jointly with the University of California, will have four times the power of the Palomar 200-inch when it is completed in 1991.

Robinson Laboratory on campus houses the Astronomy Data Processing Facility. This contains VAX and Convex C-1 computers and special equipment for processing optical and radio images. Multi-baseline VLBI data processors are operated jointly with the Jet Propulsion Laboratory. A special laboratory for the analysis of data from the Infrared Astronomical Satellite is also on campus.

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 multiply 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 biologists will find opportunities for challenging work in basic research as well as in medicine and in biotechnology.

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

Areas of Research
Research (and graduate work leading to the Ph.D. degree) is chiefly in the following fields: biochemistry, biophysics, cell biology, developmental biology, genetics, 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 chemical biology within the Division of Chemistry and Chemical Engineering.

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 transgenic mouse facility, and a state-of-the-art microchemical facility for sequencing and synthesizing biologically important macromolecules.

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

CHEMICAL ENGINEERING

The chemical engineering faculty teach and conduct research about 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:

- Cell engineering: Improved cell function for bioprocessing based on genetic and environmental manipulation. Cloned protein production. Protein targeting and modification.
- Protein engineering and processing: Design of enzymes active in organic media. Nuclear magnetic resonance studies of protein structure. Protein and polymer design for highly selective protein separations.
- Process control and design: Robust control. Decentralized control. Design for operability.
- Fluid mechanics and transport processes: Mechanics of polymeric liquids. Microstructured fluids. Transport in heterogeneous media.
- Polymer physics and rheology: Molecular understanding of polymer melt rheology. Optical properties of polymer blends. Dynamic modeling of polymer structure and rheology. Polymer diffusion in porous materials.
- Ceramics and electronic materials: Aerosol formulation of ceramic particles. Synthesis of inorganic materials in ceramics. Synthesis and characterization of electronic materials.
- Environmental chemical engineering and combustion: Physics and chemistry of atmospheric gases and aerosols. Coal combustion.
- 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.

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, an NMR spectrometer, a flow cytometer, and numerous special research facilities for 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, and molecular engineering. Active interaction exists between chemistry and other disciplines at Caltech, especially applied physics, biology, chemical engineering, geology, 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 covalent compounds, transition metal complexes, and intermetallic compounds, to investigations of the stereochemistry of organic molecules, conformations of oligopeptides, solution structures of proteins and nucleic acids, and dynamical structures of lipid bilayers by NMR spectroscopy. Active programs in other areas of spectroscopy include laser Raman, electron impact and photoelectron spectroscopy, scanning tunneling microscopy, and solid state NMR.

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 behavior of very reactive intermediates in the gas phase, in solution, and in inert matrices. 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, and nitrogen fixation. Reactions of molecules on surfaces are receiving increased attention. 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. These include projects aimed at the synthesis of natural products and of molecules required for the testing of structural theories. Efforts are also directed at the development of novel and synthetically useful chemical transformations. Recently, the division has initiated a new thrust 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 protein 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. Other areas receiving emphasis include the chemistry of membrane proteins, glycoproteins and specific receptors for a variety of external stimuli and recognition processes, and the fundamental processes of photosynthesis, immunology, and neurochemistry. 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. Theoretical techniques are also being developed to facilitate detailed understanding of electron transfer processes, energy randomization processes within molecules, and the dynamics of reacting systems.

Physical Facilities

The laboratories of chemistry consist of five units providing space for about 250 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 newly created 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, and transportation. Dealing with the function and safety of such public 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 and the escalation of urban problems 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 applied mechanics; earthquake engineering; soil mechanics and foundation engineering; finite element analysis; hydraulics, which includes hydrodynamics, hydraulic engineering, hydrology, and coastal engineering; and environmental engineering (see also environmental engineering science). In the past few years, graduate students and members of the staff have pursued a variety of research programs, including analysis of structures subjected to earthquakes and other dynamic loadings; the use of finite element methods for structural analysis; soil deformation under stress; behavior of soil models in a centrifuge; investigation of laws of sediment transportation and dispersion in bodies of water; turbulent mixing in density-stratified flows; wave-induced harbor oscillations; tsunamis; design criteria for various hydraulic structures; aerosol filtration; radioactive waste disposal; water reclamation; and ocean outfalls for thermal discharges or sewage effluents.

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 laboratory, 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

An interdisciplinary option has been established to study problems arising at the interface between neurobiology, electrical engineering, computer science, and physics. The unifying theme of this 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, the modeling of artificial neural networks, the development of massively parallel computer hardware, and recent advances in analog VLSI capabilities. Faculty in the program belong to the Divisions of Biology; Engineering and Applied Science; Physics, Mathematics and Astronomy; and Chemistry and Chemical Engineering. 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, computational hardware and software, and information theory.

Areas of Research
Areas of research include experimental and modeling studies of the visual system; the circuitry, computational function, and modeling of the olfactory cortex; the analysis of circuitry used in insect locomotion; the design and fabrication of analog VLSI for early stages in machine visual and auditory 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 hardware; and the neuron as a computational device.

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. It is the science 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 the physical and natural sciences, the objects of study by computer scientists are artificial systems, that is, structures that are purposefully designed. 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 M.S. and Ph.D. degrees in computer science are concentrated in the following areas: VLSI systems; concurrent computation; theory of computation; programming languages; semantics; programming methods and correctness; the human-machine interface, including natural language; information theory; 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.

Students have unusual opportunities at Caltech for research in very large scale integrated (VLSI) systems. VLSI is not only a powerful technology for implementing computing systems, but also an elegant medium for studying computing structures and for understanding their connection to the physical world. VLSI research at Caltech has many components, including formal design methods and theory, computer-aided design and analysis tools, and experiments with high-performance VLSI architectures.

Caltech's computer science department is unique in that it has been realized from the department's recent beginnings that programming and VLSI design should be treated as one science: the science of designing concurrent computing structures. Because of their great complexity, one cannot hope to construct reliable concurrent systems without rigorous design methods for deriving their implementation and proving their correctness. In our research in algorithms, programming notations, and semantics for concurrent computations, we are considering essentially two types of implementations: concurrent programs that run on large ensembles of communicating general-purpose automata, and direct implementation in the VLSI medium. The scale and physical characteristics of either of these media pose many interesting problems of sequencing and synchronization; these may be addressed by design disciplines such as "self-timed" systems, in which sequencing does not depend on global timing assumptions.

Research in the methods for designing computational structures addresses the complexity of computational structures by using composition to design them. In this view, a system is an elementary system or a composed system, and a composed system is a list of systems put together using a compositional operator. The study of design methods is the study of elementary systems and compositional operators. Research is conducted on the theory and application of compositional systems ranging from circuits on chips to geographically distributed systems. Of particular interest is the use of compositional methods to develop programs that will execute efficiently on a variety of concurrent computers. Specific projects deal with notations for specification and design, compiler technology, methods of reasoning about correctness and efficiency, and human interfaces that aid systematic design.

Research in software system architectures for the support of the non-computer professional is a continuing part of computer science at Caltech. The primary language of these systems is natural English, with emphasis on the users' abilities to tailor their systems to their own interests. This research includes strong experimental components, using real-life task environments.

Research in computer graphics and computer vision emphasizes the creation of realistic images. Physics is used to create realistic shapes and motions of computer models. Constraints on the physics allow controlled animation of the models. Rendering techniques that accurately simulate optics generate pictures with almost photographic realism. Computer vision is the inverse problem to computer graphics. Shape representations and constraints are equally applicable to computer graphics and computer vision problems.

Computational complexity and information theory are two basic fields of research that are growing closer. The relation between different measures of complexity, the universal bounds on the measures, and the characterization of sequential and concurrent computing in terms of the combinatorial structure of data are active fields of research.

Physical Facilities

The computer science department's computing facilities are interconnected by department networks that are part of the Internet. All department faculty, graduate students, research staff, secretaries, and librarians have terminals, personal computers, or workstations for access to these computing facilities.

Many of the department computers, including 50 Sun workstations, 30 Hewlett-Packard workstations, and four VAXs, run UNIX. Our graphics laboratory includes ten Hewlett-Packard RISC-based graphics workstations; an AT&T Pixel Machine ray-tracing engine; and a complete system for generating computer animation, using a VPR-3 one-inch videotape recorder or a digital magnetic video disk recorder. The Cosmic Cube multicomputers, and several of their commercial descendants (an Intel iPSC/1, an Intel iPSC/2, and two Symult Series 2010s) are on the department network for system and application experiments. Laser printers and color plotting devices are distributed through the offices and laboratories.

These computing facilities support a diverse collection of software used both in courses and research activities. This software includes compilers and/or interpreters for more than 20 programming languages, extensive VLSI computer-aided design and analysis tools, TeX typesetting software, and libraries of advanced computer graphics routines.

Our digital systems and VLSI laboratories are equipped with complete facilities for the construction and testing of experimental systems, including probing, testing, and packaging integrated circuits.

The computer science library subscribes to and maintains a collection of 80 journals in the computer science field. The library also includes collections of technical reports from our department and from the computer science departments of other universities, and text and reference books.

ELECTRICAL ENGINEERING

Electrical engineering at the Institute comprises physical electronics, electronic circuits, and communication. Closely allied with the computer science program and the applied physics option, it offers students the opportunity for study in the more technological aspects of a wide variety of subjects including plasma dynamics, electromagnetic radiation, quantum electronics, modern optics, new solid-state materials and devices, computer systems, control theory, signal processing, and information theory. This broad spectrum of subjects complementing the program in electronic circuits and circuit function design provides exceptional and challenging opportunities for both experimental and theoretical work.

Areas of Research and Physical Facilities

Substantial experimental laboratory facilities, housed mainly in the Harry G. Steele Laboratory of Electrical Sciences Building, are associated with each of the research fields described below.

1. Solid-State Electronics (Nicolet)—Thin films and near-surface layers are investigated from an electrical and a metallurgical point of view. Subjects currently under investigation are thin-film reactions, diffusion barriers, amorphous and metastable crystalline films, solid-phase epitaxial growth, and ion mixing. The principal tools used for experimentation are X-ray diffraction, ion implantation, and backscattering spectrometry. The properties, limitations, and ranges of application of these techniques are the subjects of additional investigations

performed with a 1-MV tandem Van de Graaf accelerator and a 400-keV ion implantation system.

2. Quantum Electronics (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 sub-micron GaAs/GaAlAs structures for optoelectronics and electronics, phase conjugate optics, applications of nonlinear optics, ultra fast ($<10^{-12}$ s) semiconductor lasers, crystal growth for image storage and processing, and optoelectronic neural networks.
3. Lasers and Guided Waves (Bridges)—The current research topics are gas laser waveguide arrays, millimeter wave light modulators, and dielectric waveguide circuits.
4. Power Electronics (Cuk, Middlebrook)—Modern problems in analysis, design, and synthesis of electronic circuits as applied to efficient conversion, control, and regulation of electrical energy. The analysis techniques are extensively verified by experiments. Projects now in progress include the design and optimization of new switching dc-to-dc converters for regulated power supplies, dc-to-ac inverters for motor drives, resonant converters, and basic studies in integrated magnetics. A firm theoretical and experimental foundation is established for investigation in a number of research areas opened up by the current studies.
5. Communications (Goodman, McEliece, Posner, Vaidyanathan)—Theoretical and computer experimental work in a wide range of information, communication, and signaling problems, including coding and modulation for channels and memories, communications switching and traffic, channel and memory capacity, digital filtering, and signal processing for speech, music, images, and radar. Current research emphases are in coding and modulation for new kinds of channels that occur in multi-user radio and guided communication, in jamming, and in magnetic recording; fundamental limits of information storage; information content and compression of graphics, video, and radar; algorithms for neural networks as communications processors; communications processing with speed constraints for high-definition television, fiber-optic carriers, and other gigabit uses; traffic modeling for mobile services, enhanced switches, and integrated services digital networks; combined modulation and coding for fiber-copper subscriber loop in telephone networks; and design and simulation of single-rate and multi-rate digital filters and filter banks to minimize the number of computational operations for a given accuracy. Possibilities of joint work in Microsystems exist.
6. Microsystems (Goodman)—Theoretical and experimental research in advanced information processing, much of which interacts with the Communications Group. The laboratory supports its theoretical work with hardware and VLSI design facilities on networked UNIX workstations, and chip fabrication via the MOSIS system. Current projects include arithmetic architectures for cryptography, error correcting code chips, expert systems for computer vision and communications network modeling, neural network VLSI memories, neural network learning, and inference chips.

7. Control (Doyle, Sideris)—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 Lab, 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.
8. Millimeter-Wave Integrated Circuits (Rutledge)—Integrated circuits and antennas for frequencies from 1GHz to 1THz. Current research projects are in developing computer-aided design software for microwave integrated circuits, network analyzers on a single chip, imaging antenna arrays for radio astronomy and radiometry, and oscillator grids for large-scale power combining.
9. Pattern Recognition (Abu-Mostafa)—The research is based on information theory, computational complexity, and neural networks. In addition to classification techniques, there is a special emphasis on the theory and methods of learning by example.
10. Optical Information Processing (Psaltis)—Research to develop optical techniques and devices for information processing. Current areas of interest include acoustooptic devices and systems, photorefractive crystals, synthetic aperture radar, image processing, pattern recognition, neural network models of computation, optical memories, and optical neural computers.

ENGINEERING SCIENCE

Advanced programs of study leading to the degrees of Master of Science and Doctor of Philosophy in Engineering Science are offered by the Division of Engineering and Applied Science. The need for these programs has developed as new frontiers of engineering have advanced to coalesce with major disciplines of science.

Areas of Research
The study program of the engineering science student at Caltech emphasizes physics, applied mathematics, biology, and those scientific disciplines that underlie the current development of technology. Its scope contains a broad range of subjects and continues to evolve and develop. Fields of study may include such topics as fluid mechanics with applications to geophysical and biomechanical problems; forced nonlinear wave phenomena; dynamics of vortical flows and structural excitation; physics of fluids; aerosol physics; rheology of biological fluids; transport in biological systems; mechanophysiology of swimming, flying, and animal locomotion; free-surface flows; naval hydrodynamics; jets, cavities, and wakes; stratified and rotating flows; tsunami and long waves in the ocean; and physical oceanography.

Physical Facilities
Laboratories are equipped with several microscope systems, laser illuminator and fluorescent imaging facilities, and high-speed cinephotomicrographic sets for biophysical and mechanophysiological studies. They are also equipped with a versatile towing tank and flow measuring devices for investigating free surface flows, propulsive devices, and fluid energy engineering.

ENVIRONMENTAL ENGINEERING SCIENCE

This interdisciplinary graduate program is concerned with the protection and control of the environment. Research and instruction stress basic studies that aim to answer such questions as: How can we improve the air quality in urban and industrial centers while maintaining clean air in pristine rural areas? How can we ensure a supply of water of adequate quality and quantity for population centers and industry? How can we safeguard the marine environment from pollution? What are the environmental consequences of alternative modes of energy production?

The academic disciplines of importance to the program include chemistry and physics of natural waters and atmospheres; physics and chemistry of particles; applied microbiology, marine biology and ecology; fluid mechanics of the natural environment; hydrology; pollutant formation and control in combustion systems; theory and design of complex environmental control systems; environmental modeling and monitoring systems; and processes of erosion, coagulation, and sedimentation. 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 fates of trace elements in the environment; coagulation and settling of particles in seawater; aerosol chemistry and physics; acid rain and fog; interactions between toxicants and marine kelp; kinetics of oxidation processes in aqueous systems; genetics and physiology of microbial transformations; in situ bioremediation processes; pollutant and particle transport in alluvial streams and groundwaters; dilution in turbulent shear flows; role of buoyancy forces in turbulent mixing; buoyant discharges in coastal waters; pollutant formation and control in combustion; regional air pollution modeling and control; and effects of air pollutants on works of art.

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.

One of the air quality laboratories is a facility located on the roof of Keck that has been specially designed for studies of gaseous and particulate pollutants, both in smog chambers and in the ambient atmosphere. In other laboratories are facilities for single particle studies of aerosol thermodynamics and chemistry, including spectroscopic analysis of individual micron-sized particles, and a variety of facilities for the study of aerosol dynamics. A drop tube furnace, a fast flow reactor, and a single particle thermogravimetric analyzer are available for studies of high temperature reactions and combustion. These laboratories are equipped with a broad range of instrumentation for the measurement of aerosol properties (differential mobility analysis, optical particle counters, condensation nuclei counters, cascade impactors, filter samplers, etc.) and for the measurement of gaseous pollutants (gas chromatography for hydrocarbons NO_x, SO_2, and O_3) as well as facilities for laser spectroscopy, reflectance spectrophotometry, and optical microscopy. Equipment is available sufficient to conduct field experiments involving measurement of atmospheric particulate matter concentration, chemical composition and size distribution, and gaseous pollutant concentration simultaneously at up to ten monitoring sites.

The water quality laboratory is equipped for chemical analysis (atomic absorption, polarography, plasma emission spectrophotometry, gas chromatography, mass spectrometry, X-ray fluorescence electrometry, high performance liquid chromatography, fluorescence spectroscopy, multiwavelength, Mössbauer, EPR, NMR, FTIR, GC/MS spectrometry, multicomponent UV-VIS spectroscopy, ion-chromotography), carbon compound identification and determination, radiologic measurements, particle size determinations (conductance, electrophoresis, electron microscopy, ultracentrifuge), microbiological measurements (biological fermenters), and kinetic measurements (T-jump and stopped-flow kinetics, ion-potentiometry, photochemical reactors, laser flash photolysis).

The hydraulics laboratory has a variety of water channels and basins appropriate for waves, sediment, and turbulent diffusion studies. A 40-meter-long glass-walled flume is equipped with dual circulating water systems for density-stratified shear flow studies. Two wave flumes and a wave basin have computer-controlled wave generators that can produce waves of specified profiles for special wave studies. Four multi-beam 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 multi-user 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 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 Kerckhoff Marine Laboratory of the Division of Biology, at Corona del Mar, is the base for work in marine ecology and coastal oceanography. A research vessel is available for field work in neighboring coastal waters. The laboratory is equipped for both kelp reproduction and growth studies, and has an extensive range of diving equipment.

An excellent library with a wide variety of current materials in environmental engineering and science, and hydraulics, is centrally located in the Keck Laboratories building.

The department provides students with access to scientific computing and word processing through various departmental computers and peripheral devices and the CADRE network of VAXs operated by the Division of Engineering and Applied Science.

ENVIRONMENTAL QUALITY LABORATORY

The Environmental Quality Laboratory is a research center for multidisciplinary, policy-oriented studies of problems related to natural resources and environmental quality. Administered within the Division of Engineering and Applied Science, the organization consists of faculty, students, and staff from various disciplines in engineering, and natural and social sciences. Since EQL is an independent research unit, faculty and students who participate in EQL activities are also associated with the appropriate degree programs. EQL research projects provide the framework for a comprehensive view of alternative solutions to natural resources and environmental control problems.

EQL research includes technical assessments, computer modeling, studies of environmental control options, policy analyses, and laboratory and field studies of important components of large-scale systems. Areas of current or recent work include:

- *Air quality, especially in the South Coast Air Basin of California* (control of sulfate and nitrate air pollutants; sources and distribution of carbon particles; visibility; development of advanced photochemical oxidant air quality models; reactive plume models; indoor air quality; effects of ozone on art works).
- *Water resources and water quality* (pollution control for coastal waters; sewage sludge disposal; acid deposition; water usage by energy industries; groundwater contamination and control).
- *Control of hazardous substances and residuals management* (toxic substances in air and water; economics and regulation).
- *Energy policy, with emphasis on environmental tradeoffs* (energy markets and pricing; energy demand and conservation; load management).

EQL contributes to the education and training for multidisciplinary environmental and natural resources research by involving predoctoral students, postdoctoral fellows, and visiting faculty members in EQL research projects. Students who desire to work in EQL apply through an appropriate degree program, such as environmental engineering science, chemical engineering, civil engineering, mechanical engineering, geological sciences, or social science.

GEOLOGICAL AND PLANETARY SCIENCES

In the Division of Geological and Planetary Sciences, faculty members study the earth and planets in order to understand their origin, constitution, and development, and the effect of the resulting physical and chemical environments on the history of life, and on man. The approach to these problems is made with strong reliance 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 up 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, chemistry, and isotopic composition of rocks formed or modified in these events. The absolute chronology can be established by measurements of radioactive isotopes. A wide variety of studies focus 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 broad-scale 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 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 modern and well equipped for instruction and laboratory work. They contain several comfortable seminar rooms and the library as well as student and faculty offices. Various computer capabilities are also distributed throughout the division. 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 design and fabrication of experimental equipment. Specimen collection and sample preparation areas are available. There are modern laboratories for chemistry (at the trace and ultra low levels), mass spectrometry (electron impact, thermal ionization, and ion microprobe), experimental petrology, infrared spectroscopy, and laser spectroscopy. 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. A field laboratory for measuring in situ stress is under development.

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.

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 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 250-station seismological network and telemetered seismic array across southern California.

State-of-the-art tunable far-infrared and infrared laser spectrometers in a newly created laser facility 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.

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 have the opportunity to 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.

HUMANITIES

Literature at Caltech spans the major periods of American, British, and European writing. Students can pursue interests ranging from Greek and 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 the Italian city-state, 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 moral and political philosophy, the philosophy of history and the social sciences, and the philosophy of the physical sciences. Members of the faculty have a variety of other interests, including philosophical problems of policy analysis, the history of philosophy, and the philosophy of psychology. Courses are given at both introductory and advanced levels.

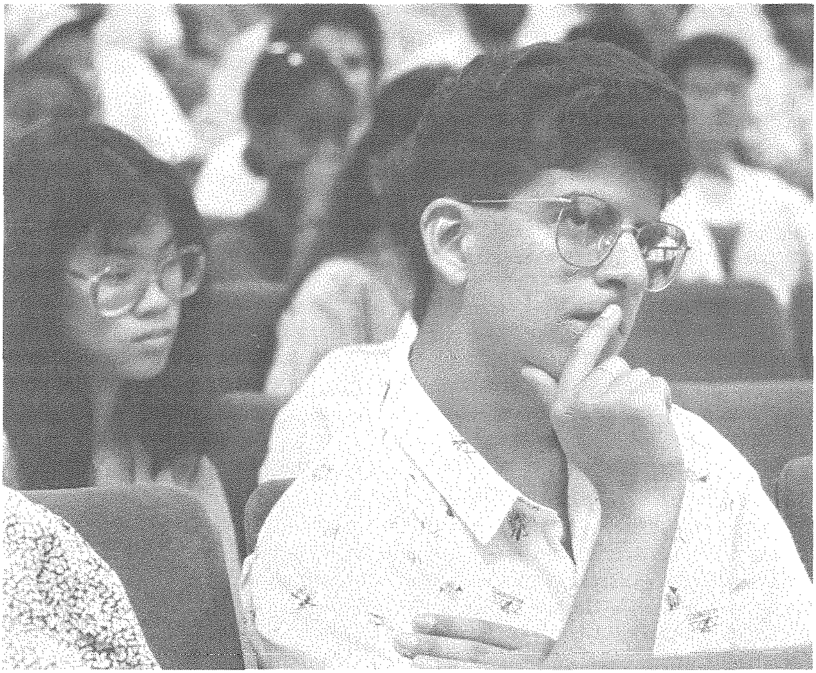
A variety of courses in classical and modern European languages and in music and art history are available. Art history classes make use of the resources of the Huntington Library and Art Gallery, the County Museum of Art, and other museums in the area.

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 U.S.; the history of the physical and biological sciences and of science in relationship to society; history of film; the growth of medieval states; late British India; taxation and economic development in France; American labor history; Chinese history and demography; and American working-class culture and labor relations. 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 the history of philosophy, philosophical problems surrounding human action, ethics, and philosophy of science.



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 131.)

MATERIALS SCIENCE

Materials scientists study relationships between the properties of materials and their internal structure, and how this structure can be controlled by methods of synthesis and by chemical composition. There are three main classes of solid materials: metals, ceramics, and polymers. Recently composite materials comprising one or more of these classes have become a topic of scientific and technical interest. The field of materials science at the California Institute of Technology is oriented toward fundamental issues in metals, semiconductors, (semiconducting and superconducting) 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 are oriented toward 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, ball-milled powders, nanocrystalline materials, and shock wave consolidated powders. The physical characteristics of interest in these systems span a wide range of mechanical, thermodynamic, and electrical properties. In all of these materials the unique structure is being characterized and its origins explored. The studies often monitor how these structures relax toward equilibrium. In addition, there is significant interaction with the faculty in applied physics concerning ion beam processing and epitaxial growth of semiconductor thin films.

The Caltech Materials Group
Materials science is inherently a cross-disciplinary field, and investigators in several options at Caltech have recognized that it is mutually beneficial to collaborate in order to promote interdisciplinary projects and to facilitate the acquisition of major equipment items that benefit many research programs. Toward this end, the Caltech Materials Group (CMG) was formed in 1985 with faculty from materials science, physics, applied physics, electrical engineering, chemistry, and mechanical engineering. Within the CMG, it is our expectation that the orientation of materials science toward the more fundamental and the orientation of physics and chemistry toward the more complex will lead to a type of materials science with a rigorous fundamental footing.

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 that have been built recently include equipment for physical vapor deposition under ultrahigh vacuum conditions, shock wave consolidation of powders, rapid solidification, 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 double crystal diffractometer, two X-ray facilities with high performance position sensitive detectors, a small angle X-ray scattering system, a Rutherford backscattering spectrometer, Mössbauer spectrometers, a differential scanning calorimeter and two differential thermal analyzers, cryogenic facilities for the characterization of superconductors, and several test systems for the measurement of mechanical properties. Caltech faculty

have just completed the installation of a state-of-the-art Philips EM 430 300-keV transmission electron microscope with high resolution as well as analytical capabilities. Two other 100-keV transmission electron microscopes and an analytical scanning electron microscope are also 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. Networked computing facilities are available.

MATHEMATICS

Areas of Research
Graduate students in mathematics may find opportunities to select areas of research from the following list of fields and subfields of mathematics that are areas of current research interest of the mathematics faculty. *Algebra:* finite group theory; *Analysis:* classical real and complex analysis, harmonic analysis, integration theory and functional analysis, and dynamical systems and ergodic theory; *Combinatorics:* block designs, coding theory, and combinatorial matrix theory; *Mathematical Logic:* recursion theory, set theory, and nonstandard analysis; *Mathematical Physics:* Schrödinger operators; *Mathematical Statistics:* sequential analysis; *Number Theory:* analytic and algebraic number theory; *Geometry and Topology:* low-dimensional and algebraic topology, Riemannian manifolds, and analysis on manifolds.

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.

The Willis H. Booth Computing Center central computing facility serves the entire campus. Computing equipment is also available in the mathematics computer laboratory on the third floor of Sloan Laboratory.

MECHANICAL ENGINEERING

The way in which the term "mechanical engineering" is being used today embraces essentially all of those engineering aspects of a project that have to do with fluid flow, heat and mass transport, combustion, power, propulsion, structural integrity, mechanical design, robotics, optimization, and systems analysis. Projects in which mechanical engineers play a large role include nuclear and fossil-fuel power plants, as well as all types of energy production and conversion installations, transportation systems, propulsion devices, and pollution control. At the Institute, many of the basic disciplines are offered that are required for such applications. They are described in the following paragraphs under the headings of Mechanical Systems and Engineering Design, Mechanics, Thermal and Fluids Engineering, and Jet Propulsion.

Mechanical Systems and Engineering Design. Activities in mechanical systems and 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, and electro-mechanical design. Analytical techniques from many fields must be used to analyze the performance, stability, and robustness of complicated systems. 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. An imaginative, practical approach is emphasized for the solution of real problems involving many areas of technology. General areas of interest include engineering system design, kinematics, robotics, and autonomous systems; and computer-aided design and simulation. Opportunities exist for analysis as well as for the design, testing, evaluation, and fabrication of prototypes. Active collaboration with the design and autonomous system activities at NASA's Jet Propulsion Laboratory, as well as those in local aerospace industries, is maintained through visits, seminars, and joint research on current problems.

Mechanics. Studies in the broad field of mechanics may be undertaken in either the applied mechanics option or the mechanical engineering option. In general, work pursued within the mechanical engineering option will have a more physical orientation. The specific areas available for advanced study closely parallel the research interests of the faculty.

Thermal Systems and Applied Fluid Mechanics. This area encompasses a broad spectrum of research activities, including convective heat transfer (packed beds, moving granular media, film cooling), radiative heat transfer, fire research, combustion of single particles and particle formation in combustion, materials processing and thin film growth, two-phase flow, cavitation, turbomachines for flow of liquids and rocket propellants, alternative fuels, aerosols, and air pollution.

Laboratory facilities are available in a large number of areas, especially computer-aided design, robotics, heat transfer, materials processing, pump dynamics, cavitation, hydrofoil analysis, and flow visualization.

Jet Propulsion. The Daniel and Florence Guggenheim Jet Propulsion Center was established at the California Institute of Technology in 1948 to provide facilities for postgraduate education and research in jet propulsion and rocket engineering. 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.

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.

High-Energy Physics. Experiments in elementary particle physics are carried out with accelerators at the Stanford Linear Accelerator Center (SLAC) and the European Center for Nuclear Research (CERN). Activities include studies of Z° decay at the new SLC accelerator at SLAC and at the LEP storage ring at CERN. A large detector to search for magnetic monopoles is under construction at the Gran Sasso underground laboratory in Italy.

A phenomenology group is concentrating on quantitative tests of quantum chromodynamics (QCD) in lepton and high transverse momentum processes, and on design and planning for the superconducting supercollider (SSC).

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 GeV range, carried out at SLAC and the Bates Linear Accelerator Center (MIT). The lower-energy experiments 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.

Nuclear and Particle Physics. This group focuses on fundamental properties of nuclei and elementary particles, particularly neutrinos. Experiments on neutrino oscillations being carried out at a nuclear reactor and on double beta decay in an underground laboratory in the Gotthard tunnel in Switzerland are designed to help understand neutrino mixing and neutrino mass. The experimental program is complemented by theoretical studies of nuclear structure and particle properties.

Cosmic-Ray and Gamma-Ray Astronomy. Measurements of energy and mass spectra of charged particles in space are carried out with detectors carried on spacecraft and balloons. The data are of interest for astrophysical phenomena such as element building in stars, astrophysical particle accelerators, and supernovae explosions. The gamma-ray astronomy program carries out astrophysical observations of solar, galactic, and extragalactic phenomena in the energy range 30 keV to 10 MeV. Studies have been undertaken with the HEAO and SMM spacecraft, and with newly developed imaging gamma-ray telescopes.

Infrared Astronomy. Astrophysical observations from 1-μm to 1-mm wavelengths are carried out with ground-based telescopes at Palomar and other observatories. This group is heavily involved in making preparations for the new 10-meter Keck observatory on Mauna Kea. Caltech has been a major participant in a recent survey of the infrared sky conducted by the IRAS satellite, from which data are being analyzed.

Submillimeter Astronomy. Star formation, interstellar gas, galaxies, and quasars are studied using the 10-meter telescope at Caltech's 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 superconducting tunnel junction detectors for use in future telescopes.

Condensed Matter Physics. Two-dimensional matter, phase transitions in two and three dimensions, phonon physics, and high-temperature superconductivity are areas of interest.

Applied Physics. Techniques of theoretical and experimental physics are applied to problems in surfaces, materials, and planets. As part of the interdisciplinary Materials Research Group, 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, and the behavior of granular material.

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.

Gravity. The program of gravitational physics shows a close interplay between theory and experiment. The limits imposed by quantum measurement theory are being explored, together with ways of reaching these limits by experiment. A new 40-meter interferometer for the detection of gravitational waves is now in operation, and design work on a multikilometer-long detector is in progress.

Theoretical Physics. The nature of elementary particles and their fundamental interactions is the focus of studies in quantum cosmology, superstring theory, large-scale astrophysics, and particle phenomenology at accelerator energies. Many astrophysical interests are pursued in collaboration with the astronomy faculty, including problems in general relativity and cosmology, in interplanetary and interstellar media, in stellar structure and evolution, in helioseismology, and in quasars, pulsars, and neutron stars.

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. Computational physics studies new systems such as parallel processors and neural networks as models of physical systems and prototypes for new computers.

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.

SOCIAL SCIENCE

Social science at Caltech offers a unique program closely integrating the fields of economics, law, political science, quantitative history, and anthropology. 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 among economics, politics, and public policy in a rigorous scientific manner. Students can use their considerable quantitative talents to great advantage in these areas.

The application of experimental methods in economics and political science was pioneered at Caltech. An exciting innovation in teaching as well as in research, experimentation enables the student to observe the operations of simplified economic and political systems and to discover how outcomes are constrained by the institutional environment in each context. The program offers a comprehensive knowledge of these economic, political, and legal institutions.

Areas of Research

The social science program is characterized by collaborative, multidisciplinary research, exploring such areas as group decision making, voting procedures, and market behavior.

Among the areas of basic and applied research in political science are (1) formal models of interdependent decision making, especially in the context of elections, congressional behavior, and cooperative committee processes, and (2) statistical analyses of the impact of economic conditions on voting, the creation and functioning of regulatory bureaucracies, redistricting, and the appropriations process in Congress.

Research in quantitative history incorporates economic and political models and statistical methods into historiography, yielding new insights into the effects of tax policy on productivity and wealth distribution, the extent of racial discrimination in the U.S., and the process that leads to the adoption of new technologies.

Current research in economics includes analysis of energy policy, tax compliance, and the effects of consumer information on the price and quality of goods and services. Faculty members are also in the forefront of the design and analysis of incentive schemes, research that promises exciting possibilities for the systematic improvement and design of institutions.

Finally, Caltech is a major center for the experimental investigation of economic and political decision making, for the development of experimental methods of analysis, and for the application of these methods to public policy.

Section Three

INFORMATION FOR UNDERGRADUATE STUDENTS

REQUIREMENTS FOR ADMISSION TO UNDERGRADUATE STANDING

The undergraduate school of the California Institute of Technology is coeducational, and undergraduates are admitted only once a year—in September. All undergraduates at Caltech are expected to carry the regular program leading to the degree of Bachelor of Science in the option of their choice. Special students who wish to take only certain subjects and are not seeking a degree cannot be accepted.

ADMISSION TO THE FRESHMAN CLASS

The freshman class of approximately 215 is selected on the basis of (a) high grades in certain required high school subjects, (b) results of College Board tests, and (c) recommendations and personal qualifications. The specific requirements in each are described below. Personal interviews with applicants and two or three of their teachers may be held at their schools when feasible. An application fee of $40 is due at the time an application for admission is submitted. The fee is not refundable, but it is applied to the first-term bills of those who are admitted and register in September.

Application for Admission

An application form may be obtained by writing to the Office of Admissions, California Institute of Technology, Pasadena, CA 91125. It is to be returned directly to the Institute.

Completed admission applications and the $40 application fee must reach the Admissions Office not later than January 1. (Application to take entrance examinations must be made directly to the College Board at an earlier date.)

High School Credits

Each applicant must be thoroughly prepared in at least 15 units of secondary school work, each unit representing one year's work in a given subject in a high school at the rate of five periods weekly. Each applicant must offer all of the units in Group A and at least five units in Group B.

Group A:	English	3
	Chemistry	1
	Mathematics	4
	Physics	1
	United States History and Government	1
Group B:	Foreign Language, Shop, additional English, Geology, Biology or other Laboratory Science, additional History, Drawing, Commercial subjects, etc.	5

The three units of English are a minimum and four units are strongly recommended.

The four-year program in mathematics should include the principal topics of algebra, geometry, trigonometric functions, and the elementary concepts of analytic geometry and probability. The program should emphasize the principles of logical analysis and deductive reasoning and provide applications of mathematics to concrete problems. A course in calculus is recommended if it is possible to arrange.

Entrance Examinations

In addition to the above credentials, all applicants for admission to the freshman class are required to take the following College Board examinations: the Scholastic Aptitude Test, the Level II Achievement Test in Mathematics, and the English Composition Achievement Test (with or without essay), plus any one of the following achievement tests: Physics, Chemistry, or Biology. The Level II Mathematics Test is designed for students who are in their fourth year of a mathematics program of the type outlined above. The Level II test does not presuppose an advanced placement course in mathematics. Note that the Scholastic Aptitude, the English, and the Level II Mathematics tests must be taken, and that the choice lies only among Physics, Chemistry, and Biology—of which one must be taken. Very rarely the applications of those who have taken the Level I instead of the Level II Mathematics Test will be considered. It should be pointed out, however, that the Institute feels it can better judge the qualifications of an applicant who has taken the Level II test, and those who have not taken it will be handicapped in the competition for admission.

The Scholastic Aptitude Test and achievement tests must be taken not later than the January College Board Series. *It is important to note that no applicant can be considered who has not taken the required tests by January, but tests taken on any prior date are acceptable.* Students should have their test results sent to the Institute as soon as they are available. Students taking the January tests should submit the results from earlier tests by February 1. A student seriously interested in the Institute would be well advised to take the Level

II Mathematics Test by the December administration if possible. No exception can be made to the rule that all applicants must take these tests.

Full information regarding the examinations of the College Board is contained in the *Bulletin of Information,* which may be obtained without charge at most high schools, or by writing to the appropriate address given below. The tests are given at a large number of centers, but if any applicant is located more than 75 miles from a test center, he or she can make special arrangements to take the tests nearer home.

Applicants who wish to take the examinations in the western United States or Canada, or in Mexico, Australia, or the Pacific Islands, should address their inquiries by mail to the College Board, P.O. Box 23060, Oakland, CA 94623-2306. Check the *Bulletin of Information* for the exact dividing line.

Candidates applying for examination in other areas should write to the College Board, P.O. Box 592, Princeton, NJ 08540.

All applications to take examinations in the United States should reach the appropriate office of the Board at least four weeks in advance of the test date. Applications for examinations to be taken abroad must arrive at least six weeks in advance. Please note that requests to take the examinations and all questions referring exclusively to the examinations are to be sent to the College Board at the appropriate address as given above and not to Caltech.

Evaluation Forms

Enclosed with the Institute's application form are two evaluation forms and the secondary school report, which the applicant should distribute to teachers who are well acquainted with his or her capabilities and preparation, with the request that they be filled out and returned directly to Caltech. These forms provide valuable information to the selection process.

Notification of Admission

Final selections will ordinarily be made and the applicants notified of the admission or rejection decision well before May 1. Most College Board member colleges have agreed that they will not require any candidate to give final notice of acceptance of admission or of financial aid before this date. After accepting an offer of admission an applicant should send in the registration fee of $100, which will be applied to the first term's bill. In the event he or she subsequently cancels the acceptance, $50 of the registration fee will be refunded if the cancellation occurs before August 1. Places in the entering class will not be held after May 1.

Deferral of Entrance

The Institute will consider requests from newly admitted freshmen for a year's deferral of entrance for such purposes as studying abroad, working, or pursuing some special interest. It is possible that not all requests will be granted: the seriousness and appropriateness of the purpose and the number of requests received will be determining factors.

Students who wish to request a year's deferral of entrance must pay the registration fee by May 1 in the normal manner and make a written request stating the purpose of postponement and the plans for using the extra year.

Early Decision Plan

The Institute will consider a few outstanding candidates who wish to make Caltech their first choice under an early decision plan. Such candidates must have taken the required College Board tests by the November test date, must have an excellent school record, and must have the thorough backing of their high school.

Applicants for admission under the early decision plan must have credentials on file by October 15 of the senior year. Early decision applicants will be notified by mid-December whether or not they have been accepted. An accepted applicant is then expected to withdraw all applications to other colleges. An applicant who is not accepted under the early decision plan will be considered without prejudice for admission at the regular time.

Advanced Placement Program

A number of high schools and preparatory schools offer selected students the opportunity to accelerate and to take in the senior year one or more subjects that are taught at the college level and cover the material of a college course. The Institute encourages students to take advantage of such courses or to supplement high school courses with mathematics and science courses at a local college. Credit for such work completed will be granted as appropriate by the faculty at the Institute at the time the student enrolls. Credit is not awarded automatically for Advanced Placement Examinations, International Baccalaureate Examinations, or for college courses completed.

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 relationships, and 4) elementary chemical thermodynamics. For those students who qualify for Advanced Placement in Chemistry, the Institute requirement of 18 units of Ch 1 abc 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 in personal interviews with the chairman of the undergraduate studies committee in chemistry, and the course instructor. 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, Freshman Mathematics. This course will cover the calculus of functions of one variable; an introduction to differential equations; vector algebra; analytic geometry in two and three dimensions; infinite series. The course will be divided into a lecture part, discussing primarily the mathematical notions of the calculus and the other topics listed above, and a recitation part, providing active practice in the application of mathematical techniques.

During the summer, entering freshmen 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 abc.

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 Ph1; students who perform 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, usually off campus, takes place during three days immediately following new student registration for the fall term. 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 faculty. Thus the new student can begin to feel at home at Caltech and share in the common agreement on intellectual and moral standards before the pressure of academic work begins.

ADMISSION TO UPPER CLASSES BY TRANSFER

The Institute admits to its sophomore or junior class a small number of students who have excellent records at other institutions of collegiate rank and who do satisfactorily on the transfer entrance examinations. Transfer students are not admitted to the senior year. No one shall be considered for admission to the undergraduate program who has completed a bachelor's degree at another institution. In general only students whose grades, especially those in mathematics and science, are well above average are permitted to take the entrance examinations. Students who have completed more than 60 semester units or 90 quarter units of college work will not be authorized to take the examinations.

Students will be allowed to apply for transfer admission only if they have completed elsewhere the equivalent of the courses required of students at the Institute. This means that applicants for transfer into the sophomore class must have completed at least 2 semesters or 3 quarters of calculus and 2 semesters or 3 quarters of calculus-based (engineering) physics at the college level. For transfer to junior-level standing, 4 semesters or 6 quarters of each of these subjects are required. A student planning to major in chemistry or chemical engineering should also have completed 2 semesters or 3 quarters of college-level chemistry.

An applicant for admission as a transfer student must complete the California Institute of Technology *Transfer Examination Request Form.* The form and instructions will be available all year. Transfer admission is granted only once per year for fall enrollment. Deadline reply dates for the *Transfer Examination Request Form* are as follows:

U.S. citizens, permanent residents, or foreign students living in and attending college in the United States: *March 15*

U.S. citizens, permanent residents, or foreign students living overseas: *March 1*

Students submitting the *Transfer Examination Request Form* must include: (a) A complete description of all college-level work completed, and all work in progress; (b) course syllabi from the college or university catalog; (c) cumulative semester or quarter units for all coursework taken; and (d) *official transcripts* of *all* college-level work completed, in a sealed envelope. The Caltech admissions office will also accept official transcripts mailed directly from a college or university registrar.

After this information has been evaluated by the admissions office, authorized students will be mailed instructions for taking the examinations. Notification of authorization or denial of authorization will be sent to all students who submit completed forms.

All authorized students are required to take the entrance examinations in mathematics and physics prepared and distributed by Caltech. In addition, an examination in chemistry covering general chemistry is required for those planning to major in chemistry or chemical engineering. Two examinations of a comprehensive character are offered in mathematics and physics. One examination in each subject covers the work of the first year; the other examination, that of the first and second years.

Examinations for admission to upper classes are given in the first two weeks in May. No other examinations for admission to upper classes will be given.

Applicants residing at a distance may take the examination under the supervision of their local college or university authorities, provided definite arrangements are made well in advance.

Information with regard to acceptance or rejection for all candidates is sent before June 20. Candidates who are admitted to the Institute must send a second official transcript of their work showing final grades received for any work in progress during the spring.

The Institute courses for which those admitted will receive credit will be determined by the Committee on Upperclass Admissions and the departments concerned, on the basis of the applicants' previous records.

It is not possible to give definite assurance that a transfer student entering the sophomore year will graduate in three years or that one entering as a junior will graduate in two years. Much depends on the amount and nature of the credit granted at the time a student registers in September and on the possibility of fitting deficiency make-ups into the regular schedule. A preliminary credit statement will be sent to admitted students by mid-August.

The first-year chemistry course at Caltech differs from those given at many other colleges because of the inclusion of a substantial amount of quantitative analysis in the laboratory work. A transfer student who has had a one-year college course in inorganic chemistry and qualitative analysis will be considered to have met the first-year chemistry requirements, provided, of course, that grades have been satisfactory. Those wishing to major in biology, chemistry, or geology will be required to take certain portions of freshman chemistry if they have not had the equivalent laboratory work elsewhere. Transfer students entering the junior year in chemistry will be able to take the sophomore organic chemistry course during their first year at the Institute.

All transfer applicants must arrange to have their scores on the Scholastic Aptitude Test (SAT) of the College Board sent to Caltech. If they have taken the SAT in previous years, these scores will be acceptable; but applicants must instruct the College Board (see address on page 77) to send the scores to the Institute. If the SAT has not been taken previously, it must be taken by the March series at the latest. College Board Achievement Tests are not required of transfer applicants.

Students whose native language is not English and who attend schools abroad will be required to take the Test of English as a Foreign Language (TOEFL). This test is an Educational Testing Service test and is given all over the world four times a year. This test must be taken by the February series at the latest. Full information on how and where to take the test should be obtained from ETS. Students living in and attending school in the United States are not required to take the TOEFL.

It is not possible to answer general questions regarding the acceptability of courses taken elsewhere. The nature of the work at the Institute is such as to demand that all courses offered for credit be scrutinized individually. In case the standard of the work taken elsewhere is uncertain, additional examinations may be required before the question of credit is finally determined.

Transfer students are required to pay a registration fee of $10 upon notification of admission to the Institute. If the application is cancelled, the registration fee is *not* refundable unless cancellation is initiated by the Institute.

The 3-2 Dual Degree Plan

The California Institute of Technology has an arrangement whereby students enrolled in certain liberal arts colleges may follow a prescribed course for the first three years and then transfer into the third year of the engineering option at the Institute without further formality, provided that they have the unqualified recommendation of the officials at the liberal arts college that they are attending. After two full years' residence at the Institute and after satisfactorily completing all the remaining work required for a bachelor's degree in engineering, they will be awarded a Bachelor of Arts degree by the college from which they transferred and a Bachelor of Science degree by the Institute. Application for admission at the freshman level under this dual degree plan should be made to the liberal arts college.

The colleges with which these arrangements exist are Bowdoin College, Brunswick, Maine; Bryn Mawr College, Bryn Mawr, Pennsylvania; Grinnell College, Grinnell, Iowa; Occidental College, Los Angeles, California; Ohio Wesleyan University, Delaware, Ohio; Pomona College, Claremont, California; Reed College, Portland, Oregon; Wesleyan University, Middletown, Connecticut; Whitman College, Walla Walla, Washington.

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.

ROTC

Through arrangements with the University of Southern California (USC), an Air Force Reserve Officers' Training Corps program is available to qualified full-time Caltech students on a competitive basis, and an Army Reserve Officers' Training Corps program is available through the extension program of the University of California at Los Angeles (UCLA). The Air Force (AFROTC) program is a two- or four-year program available to juniors or freshmen. Successful completion of this program leads to a commission as a Second Lieutenant in the Air Force. The four-year program for freshmen must be applied for by December 1 of the year prior to entering college. The deadline for the other program is in the year prior to entering the program. Air Force ROTC offers two types of scholarships, Type I and Type II. The application process is the same for each scholarship type. Type I scholarship provides full tuition, required fees and books, uniforms, and $100 a month. The entitlement for a Type II scholarship is the same except the tuition is capped by Air Force ROTC. Academic units earned in this program count toward fulfillment of graduation requirements. Students desiring this credit should request that an official transcript be forwarded to Caltech. For additional information on this program, contact the Department of Aerospace Studies (AFROTC) at the University of Southern California, Los Angeles, CA 90089, (213) 740-2670. The Army ROTC offers four-, three-, and two-year scholarships that range from $200 to $5,000 a year, depending on type of award and tuition costs. High school seniors must complete applications for national competition before December 1 prior to the year they plan to attend. Completion of the program leads to a commission as a Second Lieutenant in one of seventeen specialties in the Army Reserve, National Guard, or Regular Army. For additional information, contact the Department of Military Science, UCLA, Men's Gym, #142, Los Angeles, CA 90024, (213) 825-7381.

REGISTRATION REGULATIONS

Procedures

Students must register in person on the dates specified in the academic calendar. Registration material is to be picked up at a location designated by the Registrar, and returned to the registration area when completed. Students are not registered until they have both

- turned in a signed registration card with their approved study list, *and*
- made satisfactory arrangements with the Office of Student Accounts 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 leave of absence. If continuity is broken by withdrawal without leave, 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 Dean.

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.

Leave of Absence

Leave of Absence
A leave of absence 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 leave of absence 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 leave is for one year or less, and (c) the leave extends over a period which includes at least one full term.

The Dean or Associate Dean may also grant a leave of absence for medical reasons provided the petition is approved by the Director of Health Services or the Director of Counseling Services. Return from a medical leave 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 of absence for medical reasons will maintain the same academic standing which he or she had at the beginning of the leave.

Involuntary Leave of Absence
The Dean of Students may place a student on an involuntary leave of absence 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. An involuntary leave may include a specific date after which the student may return or it may be indefinite as to term. In the latter case the Dean of Students may stipulate conditions which 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, who may review all leaves of absence.

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 leave of absence, 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 will be noted on the record. The record will also indicate if a leave of absence 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. Students who are registered for summer research or reading will not be required to pay tuition for the units.

SCHOLASTIC REQUIREMENTS

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

Ineligibility 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 27 or more units 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 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 Registration Day 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 will be granted only under exceptional conditions.

Departmental and Option Regulations

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 G.P.A. 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
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 an average of 33 units per completed term (excluding summers) in residence or has not completed an average of 30 units in the three most recent terms in residence.

Graduation Requirement
To qualify for graduation a student must complete the prescribed work in one of the options with a passing grade in each required subject and with a grade-point average of 1.9. A grade of F in an elective course need not be made up, provided the student has received passing grades in enough other accepted units to satisfy the minimum total requirements of the option.

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

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.

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
At the beginning 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 preregistration for the following year.

An undergraduate may be allowed to major in two options for the Bachelor of Science degree. As a general rule, the two options should not be in the same division. The student must obtain the approval of the Curriculum Committee prior to the beginning of the senior year. He or she will then be assigned an adviser in each option.

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

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 three terms of physical education. This requirement may be satisfied entirely or in part by participation in intercollegiate athletics, successful completion of a physical education class, or successful completion of a student-designed program of physical fitness.

Participation as a bona fide member of an intercollegiate team for the period covered by a sport in a given term satisfies the requirement for that term. Students dropping from an intercollegiate team before the end of the term or the season must enroll in a physical education class immediately, if they wish to receive credit for physical education.

A broad program of instruction is provided each term. Enrollment in classes is conducted in the gymnasium and at the pool on the day of General Registration. Students planning to enroll in sailing must pass a swimming test. 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 activity.

Student-designed programs of physical fitness are submitted in writing to the Department of Physical Education during the first week of each term. These programs must provide for participation in vigorous physical activity at least three days per week. The programs may consist of individual or group participation and may include intramural sports participation. At the end of the term the student files a brief written report with the Department of Physical Education reviewing his or her accomplishment of prestated objectives. It is assumed that students proposing their own programs of physical fitness are competent in these activities.

UNDERGRADUATE EXPENSES

For freshmen applying for admission, there is a $40 application fee. This fee is not refundable, but it will be applied to tuition fees upon registration.

A registration fee, $100 for freshmen and $10 for transfer students, is payable upon notification of admission. This fee is not refundable, but it will be applied to tuition fees upon registration. Housing contracts must be submitted to the Master's Office by the date specified in the instructions accompanying the contract.

Expense Summary 1990–91

General:	
General Deposit	$ 25.00[1]
Tuition	13,300.00
Student Body Dues, including *The California Tech*	60.00[2]
Assessment for *Big T*	30.00[2]
	$13,415.00
Other:	
Student Housing: (Rates are subject to change)	
Room	2,239.38
Board (provides 10 meals per week while Institute is in session)	2,021.25
Dues	105.00
Books and Supplies (approx.)	585.00
Personal Expenses (approx.)	1,140.00
Meals not on Board contract (approx.)	1,161.00
	$7,251.63

[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 1990–91 together with the dates on which these charges are due. Fees are subject to change at the discretion of the Institute.

	First Term	*Fee*
September 25, 1990 *(Freshmen)*	General Deposit	$ 25.00
	Tuition	4,434.00
October 1, 1990 *(All Others)*	Associated Student Body Dues	20.00
	Assessment for *Big T*	10.00
	Room and Board (for on-campus residence)	1,420.21
	Student House Dues and Assessment	35.00
	Second Term	
January 7, 1991	Tuition	$4,433.00
	Associated Student Body Dues	20.00
	Assessment for *Big T*	10.00
	Room and Board (for on-campus residence)	1,420.21
	Student House Dues and Assessment	35.00
	Third Term	
April 1, 1991	Tuition	$4,433.00
	Associated Student Body Dues	20.00
	Assessment for *Big T*	10.00
	Room and Board (for on-campus residence)	1,420.21
	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	$ 123.00
Minimum tuition per term	1,230.00
Audit Fee $123.00 per lecture hour, per term.	

Other Items of Interest

Refunds

Students withdrawing from the Institute during the first three weeks of a term are entitled to a partial refund of tuition based on the period of attendance. The schedule for the specific percentage of tuition to be refunded for specific days of attendance is shown below. The days in attendance are the number of days counted from the first day of the term to:

- date of approval of the request by the Dean of Students for *withdrawals.*

Withdrawal Tuition Refund Schedule
Tuition is refunded according to the following schedule:

Days	*Percent of tuition due the Institute*	*Days*	*Percent of tuition due the Institute*
1–7	20.00	15	40.00
8	30.67	16	41.33
9	32.00	17	42.67
10	33.33	18	44.00
11	34.67	19	45.33
12	36.00	20	46.67
13	37.33	21	48.00
14	38.67	22	100.00

- registration for reduced units is approved by the Undergraduate Academic Standards and Honors Committee or the Registrar. For students enrolled in less than 36 units for the term, a tuition credit for the difference between the charge for 36 units and the appropriate charge for the reduced units will be applied to the student's account. This tuition credit will only be made for reduced units as of the published Add Day of each term. However, if tuition credit has been applied to students' accounts for reduced units, any subsequent increase in tuition units will result in the appropriate tuition charge for the increased number of units retroactive to the beginning of the academic term.

The Financial Aid Office is notified of refunds for aid recipients. The amount of refund is determined by the refund schedule stated above.

In the case of a withdrawal, the portion of refund to be returned to Title IV funds is as follows:

$$\frac{\text{Total Title IV aid (excluding CWS) for payment period}}{\text{Total aid awarded (excluding CWS) for payment period}}$$

The distribution order of the Title IV portion of the refund is as follows:

1. Perkins Loan
2. SEOG
3. Pell
4. Stafford
5. SLS
6. PLUS

The non-Title IV portion will be distributed as appropriate, first to outside donors, as required, then to Caltech grant, scholarship, or loan, depending on the composition of the aid package. These distributions will occur as credits to the appropriate aid funds from the student's Caltech account.

If a Stafford/PLUS/SLS disbursement was credited to the student's account during the academic year, some of the loan proceeds may be attributed to a payment period subsequent to the one in which the student withdrew, and require a return disbursement to the lender. This determination will be made prior to the above refund calculation.

Repayment
Upon withdrawal, overpayment of aid in excess of direct charges and allowable indirect charges is calculated as follows:

	Direct Charges
Tuition and fees	actual charges
Room and board	prorate by number of weeks attended times actual weekly cost (daily room rate times 7, plus daily board rate times 5)

Board contracts are prorated according to the number of days a student has been on campus. Room contracts are charged on a term basis for all students. Early termination of a room contract will be granted only with the approval of the Master of Student Houses.

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 $30 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 $25, 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 personally turned in 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.

Honor System Matters
Monies owed to the Institute resulting from a Board of Control decision may be collected through Student Accounts, 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 Master of Student Houses, 0-54, California Institute of Technology, Pasadena, CA 91125.

Special Fees
Students taking the Summer Field Geology course (Ge 123) 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 Office of Student Accounts.

FINANCIAL AID

Caltech believes that qualified students who wish to attend Caltech should not be prevented from doing so for financial reasons. The Institute is therefore strongly committed to meeting the full demonstrated financial need of students whose families cannot afford the total cost of a Caltech education.

Financial need is the difference between the 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 U.S., Mexico, or Canada.) Caltech's estimate of a family's ability to contribute is determined on a yearly basis from the information provided on the financial aid application. The information is analyzed using a federally mandated formula called Congressional Methodology.

Eligibility for each type of assistance varies, depending upon the source of funds. Most students who attend Caltech receive 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 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 do not have to be accepted for admission to Caltech before applying 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.

Although Caltech 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. In addition to direct financial assistance, information is offered about education payment plans and financial-planning resources. (For information on non-need-based scholarships and prizes, see pages 98 and 100–104.)

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, application procedures, and financial aid awards and programs, contact the Financial Aid Office, California Institute of Technology, 12-63, Pasadena, CA 91125, or call (818) 356-6280.

HOW TO APPLY FOR FINANCIAL AID

- *Early Decision Admission Candidates* should file an Early Version Financial Aid Form (FAF) with the Caltech Financial Aid Office between October 15 and November 15, 1990. Preliminary estimates of financial aid eligibility will be issued with the admissions offer. The application procedures for *freshman admission candidates* (below) must be completed before an official award can be offered.
- *Freshman Admission Candidates* should submit a completed Financial Aid Form (FAF) to the College Scholarship Service (CSS) for processing between January 1 and February 1, 1991, and designate Caltech as a recipient. California residents must use the Student Aid Application for California (SAAC) instead of the FAF and apply for a Cal Grant. Conditional awards will be issued with offers of admission. Awards will become final after tax returns and all other requested documents are received by the Financial Aid Office and any necessary award adjustments are made.
- *Returning Students* should obtain a copy of the SAAC and accompanying documents from the Caltech Financial Aid Office. The SAAC should be submitted to the College Scholarship Service by March 2, 1991. California residents must apply for a Cal Grant, if eligible. Accompanying documents should be submitted directly to the Financial Aid Office by May 1, 1991.
- *Transfer Admission Applicants* should submit a completed FAF or SAAC to the College Scholarship Service by March 2, 1991. California residents must apply for a Cal Grant by the March 2 deadline. Conditional awards will be issued with offers of admission. Awards will become official after tax returns and all requested documents are received by the Financial Aid Office and any necessary award adjustments are made. Financial aid transcripts from each college previously attended are required.
- *International Student Applicants* (with the exception of Canadians and Mexicans, who should follow the procedures for the appropriate domestic students listed above) must submit to the Financial Aid Office the Foreign Student Financial Aid Application and Certification of Finances. This must be done at the time of application for admission to Caltech. Conditional awards will be issued with offers of admission. Awards will become official after tax returns and all other requested documents are received by the Financial Aid Office, and any necessary award adjustments are made. Those offered assistance will be eligible to apply for aid in subsequent years. International students who do not apply for aid at the time of admission, or who are denied aid, will be ineligible for aid during any other academic period while they are undergraduates at Caltech. (Canadians and Mexicans are exempt from this rule.)

- *Returning International Students* should file the Foreign Student Financial Aid Application and Certification of Finances in accordance with the dates listed for *Returning Students* (above).

Please note: In addition to the application forms described, all financial aid applicants must submit signed copies of their parents' and their own federal income tax returns, complete with all schedules. If a tax return will not be filed, a statement to that effect will be required. International students must submit translated returns from their country of nationality and/or from the country where their parents are employed.

TYPES OF AID AVAILABLE

Once financial need has been determined, that need can be met either by a single type of aid or by a combination of grants or scholarships, student employment, and loans. Together, they make up a financial aid "package," which is simply a combination of awards. For the 1990–91 academic year, students will typically receive $4,250 in a combination of work and/or loan, with any remaining need being met with grant money.

Grants and Scholarships

Caltech Grants are awarded from an institutional fund or endowment specifically established for the purpose of assisting undergraduates. The amount of the award depends on financial need.

"Name" Scholarships are awarded to undergraduates with financial need. Funds are given to the Institute by individuals or organizations for scholarship purposes, and are named by or for the donor. No separate application is required.

Pell Grants and Supplemental Educational Opportunity Grants (SEOG) are federally funded grants. All eligible students are required to apply for Pell Grants on the SAAC/FAF and to submit to the Financial Aid Office the Student Aid Reports received from the processor.

Cal Grants are awarded by the California Student Aid Commission to California residents. All eligible California residents are required to apply on the SAAC application.

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

Employment

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. Because all income earned during the academic year may be considered as a resource for those receiving financial aid, students should notify the Financial Aid Office when they begin employment during the academic year. 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 commence employment until second term. Freshmen must receive permission from the Dean of Students prior to commencing employment.

College Work-Study is a federally funded program that provides part-time employment for students with demonstrated financial need. College Work-Study jobs are available on campus and at JPL. Interested students should contact the Career Development Center. *Summer College Work-Study* may also be available.

The Foreign Student Employment Program is funded by the Institute to provide part-time employment for international students with demonstrated financial need. Jobs are available on campus or at JPL. *Summer Foreign Student Employment Program* funding may also be available.

Loans

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 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. Perkins Loans are limited to a total of $4,500 during the first two years of undergraduate study, a total of $9,000 for all undergraduate study, and a maximum of $18,000 for the entire undergraduate and graduate career. Information concerning deferment, postponement, and cancellation will be provided to each borrower on the loan promissory note.

Caltech Loans are made from funds provided by many sources, and are used to supplement the Institute's 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 9 months after leaving school or dropping below half-time status. Interest is then charged at a rate of 5 percent on the unpaid balance until the loan has been repaid in full. As with Perkins Loans, if the student transfers to another institution or attends graduate school, here or at another institution, no payments need be made on the principal or interest as long as half-time attendance is maintained at the other institution. More specific information is provided to each borrower on the promissory note.

Stafford Loans are federally insured loans available through banks and other lending institutions. Stafford Loans are awarded to meet demonstrated financial need. The current interest rate is 8 percent, increasing to 10 percent with the fifth year of repayment. A separate application form in addition to the FAF or SAAC is required, and may be obtained from the lender or the Financial Aid Office. The current loan maximums are $2,625 per year for undergraduates in the first two years of study, and $4,000 per year for subsequent undergraduate years. The aggregate undergraduate Stafford limit is $17,250. Graduate students may borrow $7,500 yearly, with an aggregate limit of $54,750 including undergraduate loans.

Supplemental Loans for Students allow independent undergraduate or graduate students to borrow up to $4,000 per year with an aggregate limit of $20,000. Loans have a variable interest rate, adjusted yearly. For the 1989–90 academic year, the interest rate was 12 percent. Repayment generally begins within 60 days of when the loan is made. A separate loan application is required. Specific details on the SLS Loan, applications, and repayment and deferment information are available from lenders or the Financial Aid Office.

PLUS Loans are federal loans that help parents of dependent undergraduates prorate payment of their contribution toward educational costs. A parent may borrow up to $4,000 a year for each dependent undergraduate, with an aggregate limit of $20,000 for each student. Loans have a variable interest rate, adjusted yearly. For the 1989–90 academic year, the interest rate was 12 percent. Repayment generally begins 60 days after the loan is made. A separate loan application is required. Specific details on the PLUS Loan, applications, and repayment and deferment information are available from lenders or the Financial Aid Office.

No-Need Scholarships

A number of scholarships are available to *returning* students regardless of financial need. Each year the Committee on Scholarships and Financial Aid recommends a number of the Institute's most academically talented freshmen, sophomores, and juniors for Merit Awards for the following year. Recommendation for these awards is made solely on the basis of academic merit. These awards are made from the Caltech Prize and Carnation Scholarship endowments. The John Stauffer Scholarship is also awarded to a student with a chemistry related major. In 1989–90, 51 students received Merit Awards in the amount of $3,000 to $12,300. The honor is recorded on transcripts and listed in the commencement bulletin when the scholars graduate.

Several corporations, including General Motors and Northrop, 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.*

Satisfactory Academic Progress

In order to continue receiving financial aid at Caltech, students must maintain satisfactory academic progress toward completion of the baccalaureate degree as defined on page 104. Approval for reinstatement by the Undergraduate Academic Standards and Honors Committee or the Dean of Undergraduate Students (as described on page 85) shall re-establish 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 part-time students). Exceptions may be approved after submission of a petition to the Financial Aid Office.

Refund and Repayment Policy

Caltech has established an equitable refund policy for students who find it necessary to withdraw from the Institute.

Withdrawal from the Institute:
Students who officially withdraw from the Institute during an academic term will receive a tuition refund based on the schedule published on page 92. Students living in Caltech housing may also be eligible for a partial refund from the Housing Office.

When granting refunds to financial aid recipients, it is Caltech's policy to reduce the aid award by the amount of the refund and any adjustments in the actual living costs. Therefore, an aid recipient's refund is, in most cases, returned to the original aid account.

An overpayment or overaward occurs when a student receives more aid than he or she is eligible to receive. Therefore, the Financial Aid Office will compare actual costs to aid disbursed in accordance with federal guidelines. If aid disbursed exceeds costs, the student may be responsible for the overpayment. Any overpayment will be charged to the student on his or her student account. Additional information is available in the Financial Aid Office.

Dropping a Course:
A student's financial aid package will be adjusted to reflect any tuition adjustment made by the Student Accounts Office. 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 expectation. Additional information is available in the Financial Aid Office.

Financial Payment Plans

The following organizations offer financial payment plans to help cover the costs of education at Caltech:

- Academic Management Services, Inc., 1110 Central Ave., Pawtucket, RI 02861 (800-556-6684), offers a nine-month annual budget payment plan. Payment under this plan begins June 1. Cost of this program is a $45 annual fee. A Life Benefit Coverage is provided at no additional cost.
- EFI Fund Management Corporation, 2700 Sanders Road, Prospect Heights, IL 60070 (800-323-8399), offers a ten-month budget plan for the annual cost of tuition, fees, and room and board, with an option for a two-, three-, or four-year program offering 12 payments a year after the initial year. Payment under this plan begins in June. Cost of this program is a $30 annual fee.
- Knight Tuition Payment Plans, 855 Boylston Street, Boston, MA 02116 (617-267-1500) or (800-225-6783), makes available a monthly repayment plan. The Insured Tuition Payment Plan allows the payment of university expenses in a monthly payment plan while the student is attending school. Payments to the university are made for the student from an individual money market account established in the student's name and insured by FDIC. No interest is charged. Life insurance is automatically scaled to cover future payments if applicable. The cost of this program is a one-time nonrefundable initial fee of $50.

- The Tuition Plan, Inc., 57 Regional Drive, Concord, NH 03301-0738 (800-343-0911), offers a prepayment program that provides monthly budgeted expenses in advance of each school term. Cost of this plan is a $45 initial fee, and insurance is available to insurable parents (at no additional cost).

PRIZES

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.

Fritz B. Burns Prize in Geology

This prize is awarded to a junior or senior who has demonstrated both academic excellence and the greatest 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. 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.

Donald S. Clark Memorial Awards

From a fund contributed by the Caltech Alumni Association, annual awards of $500 are made to two juniors in engineering options in recognition of service to the campus community and grade point averages equal to or greater than those 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 Master's Cup

Two awards, selected by the Deans 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.

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 chairman 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 five percent of his or her class who shows outstanding promise for a creative professional career. The student is selected by the division chairmen 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 fifteen 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 chairmen 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 bio-organic 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 $500 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 without prior notification, consists of a cash award and a certificate.

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 chairman 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 of $2,000 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.

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 their 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 graduating senior who has shown unusual interest in and talent for history.

H. J. Ryser Scholarships

The H. 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.

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.

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, freshman, sophomore, and junior students, 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 $750, funded from membership dues, to a senior selected for an outstanding piece of original scientific research. The student is selected by the division chairmen and the deans, together with the Undergraduate Academic Standards and Honors Committee.

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 the 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 5.

Institute Requirements, All Options

	Course	*Units*
1.	Freshman Mathematics (Ma 1 abc)	27
2.	Sophomore Mathematics (Ma 2 abc[1])	27
3.	Freshman Physics (Ph 1 abc)	27
4.	Sophomore Physics (Ph 2 abc[2] or Ph 12 abc)	27
5.	Freshman Chemistry (Ch 1 abc)[3]	18
6.	Freshman Chemistry Laboratory (Ch 3 a)[4]	6
7.	Additional Introductory Laboratory	6
8.	Humanities Courses (as defined below)	36
9.	Social Sciences Courses (as defined below)	36
10.	Additional Humanities and Social Sciences Courses	36
11.	Physical Education	9

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), Bi 10 (6 units), Ch 3 b (6 units), Ch 4 ab (6 units per term), CS/EE 11 (6 units), E 5 (6 units), Ph 3 (6 units), Ph 4 (6 units), or a more advanced laboratory course.

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, and, with certain restrictions, languages and linguistics) 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 granted credit by petition to the Humanities or Social Science faculty. 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 20 or below in the catalog that require from 4,000 to 6,000 words of essay writing a term. Successful completion of two terms is a prerequisite for advanced humanities (numbered above 20), but *not* for introductory social sciences. These courses may be taken in any two terms of the freshman year.

All incoming freshmen are required to take a diagnostic English examination before the beginning of first term. Students who fail to demonstrate a sufficient command of the English language are not allowed to enter

[1] *One term from the following courses may be substituted for Ma 2 c: Ma 112 abc, Ma 144 ab, AMa 153 abc.*

[2] *One term from the following courses may be substituted for Ph 2 c: Ph 12 c, APh/ME 17 c, Ch 21 c.*

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

Freshman Humanities courses until they successfully complete a remedial English program to be offered during the first term and repeated in the second term if necessary. This program does not count toward the 108-unit requirement or toward the requirement for Freshman Humanities. Students whose English language skills are found to be sufficient but who fail to demonstrate a capacity to write a coherent essay are required to take a composition course (Hum 13), which they must complete successfully before being allowed to proceed to the rest of the Freshman Humanities menu of courses. A student will be given Freshman Humanities credit for the course once only, though the student may have to take it more than once to reach the standard required for entry to other Freshman Humanities courses, in which case general Institute credit will be given for the repeated quarters.

A student must take 18 units of advanced humanities courses. Courses that count toward the advanced humanities requirement are marked in the catalog by an asterisk. Courses numbered from 21 through 199 without the asterisk can be taken to fulfill the final 36 units of the 108-unit HSS requirement unless otherwise noted. 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. In addition, the fifth and sixth terms of a language count toward the 18-unit advanced humanities requirement.

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: SS 33; Political Science: PS/SS 12; Psychology: Psy 10, Psy 12; 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. Ec 11 may be used as the introductory course for PS/SS 122 and SS 140. SS 13 can serve as the introductory course for Ec 129, PS 119, and PS/SS 125.

Courses that are cross-listed between Humanities and Social Science disciplines (e.g., psychology and literature, or history and economics) will not count toward either upper-division requirement unless so defined in the catalog.

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 abc	General and Quantitative Chemistry (3-0-3)	6	6	6
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
	Additional Electives[3]	x	x	x
PE	Physical Education[4]	3	3	3

x—Except for the minimum laboratory unit requirement, the number of units chosen here is optional. If the student chooses no electives except physical education and takes the minimum permissible laboratory courses, the total unit load will be 42 for two terms and 39 for one term. 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 upper-class 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), CS/EE 11 (6 units), E 5 (6 units), Ph 3 (6 units), Ph 4 (6 units), or a more advanced laboratory course.*
[3]*A partial list of electives particularly recommended for freshmen includes the following: APh/MS 4, Ay 1, Bi 5, Bi 8, ChE 10, CS/EE 4, CS 10, E 1 a, E 1 b, EE 5, Env 1, Ge 1, Ph 10, Ph 20, Ph 21, Ph 22.*
[4]*Three terms (9 units) of PE are required for the B.S. degree. Students need not elect to take the required PE in the freshman year. It may be taken in any three terms before graduation.*

Applied Mathematics Option

The undergraduate option in applied 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, AMa 95 abc, and AMa 101 abc.
2. One of the following (or an approved combination): AMa 98 abc, AMa 151 abc, AMa 152 abc, AMa 153 abc, AMa 181 abc, or AMa 104 and AMa 105 ab.
3. One of the following (or an approved combination): Ma 107 and Ma 109

ab, Ma 110 abc, Ma 120 abc, Ma 121 abc, Ma 122 abc, Ma 126, Ma 127 ab, Ma 151 abc.
4. One 27-unit 100 or higher level course in science or engineering not in AMa 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		
Second Year		*1st*	*2nd*	*3rd*
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ma 5 abc	Introduction to Abstract Algebra (3-0-6)	9	9	9
	Humanities Electives	9	9	9
	Electives	9	9	9
		45	45	45
Third Year				
AMa 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives	9	9	9
	Electives	27	27	27
		48	48	48
Fourth Year				
AMa 101 abc	Methods of Applied Mathematics (3-0-6)	9	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 who has a grade-point average 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 24, Ph 3, Ph 5, Ph 6, Ph 7.
2. APh/ME 17 abc, APh 50 abc, and Ph 106 abc.
3. AMa 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, ChE 126, CS/EE 53, CS/EE 54, MS 123, MS 130, MS 131.
5. 27 additional units of APh courses numbered over 100, which must include one of the following: APh 101 abc, APh 105 abc, APh 114 abc, APh 156 abc, APh 181 ab, APh 190 abc, or the sequence APh/EE 130, 131, 132. None of these courses may be taken on a pass/fail basis. 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.

Typical Course Schedule

		Units per term		
Second Year		*1st*	*2nd*	*3rd*
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
	Humanities Electives	9	9	9
	Laboratory Electives[1]	6	6	6
APh 17 abc	Thermodynamics (3-0-6)	9	9	9
	Other Electives	9	9	9
		51	51	51
Third Year				
APh 50 abc	Applied Physics (3-0-6)	9	9	9
APh 110 abc	Topics in Applied Physics	2	2	2
AMa 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives	9	9	9
	Other Electives[2]	18	18	18
		50	50	50

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

Fourth Year

APh 78 abc	Senior Thesis, Experimental[1]	6	6	6
or				
APh 77	Laboratory in Applied Physics[1]	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 4, option requirements.*
[2] *See item 5, 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
APh 23, APh 24, Ge 1, Bi 8, Ay 1, EE 14 abc, EE 90 abc, Ma 5 abc, MS 15 abc

Third Year
APh 77, Ph 77 ab, EE 114 abc, Ch 6 ab, Ge 154 abc, APh 100, ME 19 abc

Fourth Year
APh 77, APh 100, Ae/APh 101 abc, APh 105 abc, APh 114 abc, AMa 101 abc, AMa 104, AMa 105 ab, Ch 125 abc, Ph 125 abc, Ph 129 abc, Ph 77 ab

More Specialized Courses
APh 156 abc, APh 181 ab, APh 190 abc, APh/EE 130, AM 135 abc, ChE 103 abc, ChE 126 abc, EE 91 abc, EE 155 abc, Ge 104 abc, Ge 166

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, 22, 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 101, 14 units of Ay electives (excluding Ay 1), Ph 3, Ph 5 or 6, Ph 7, Ph 98 abc or Ph 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		
Second Year		*1st*	*2nd*	*3rd*
Ph 2 abc or	Waves, Quantum Mechanics and Statistical Physics (4-0-5)	9	9	9
Ph 12 abc[1]	Quantum and Statistical Mechanics (3-0-6)			
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ay 20	Basic Astronomy and the Galaxy (3-2-6)	11	–	–
Ay 21	Galaxies and Cosmology (3-0-6)	–	–	9
Ph 3, 5, 6, 7	Physics Laboratory[2]	0-6	6	0-6
	Humanities Electives	9	9	9
	Electives[3]	0-9	3-6	12-15
	Suggested total number of units	38-53	36-39	48-57
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

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

[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.*

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: AMa 95[1], Ay 22, Ay 110, Ay 121, Ay 122, Ay 123, Ay 124, Ay 125, Ay 126, Ay 127, Ay 128, Bi 1, EE 5, EE 14, EE 90, EE 157, Ge 1, Ge 4, Ge 101 a, Ge 131, Ge 153, Ge 154, Ge 167, Ma 5, Ma 112, Ph 77, Ph 125[1], Ph 129, Ph 136[1].

[1] *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 at the Institute. 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 premedical adviser, Dr. Marlene Coleman.

Option Requirements

1. Specific courses: Bi 8, Bi 9, Bi 11, Bi/Ch 110 abc, Bi 122, Bi 123, Bi 150, and Ch 41 abc.
2. An additional 52 units of Bi courses. At least 10 of these units must be in Bi 22 or laboratory courses (Bi 10, Bi 161, Bi 162, Bi 180).
3. Passing grades must be earned in a total of 486 units, including the courses listed above.

Recommended Course Schedule

		Units per term		
Second Year		*1st*	*2nd*	*3rd*
	Humanities Electives	9	9	9
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
Bi 8	Introduction to Molecular Biology (3-3-6)	–	12	–
Bi 9	Cell Biology (3-0-6)	–	–	9
	Electives	9-15	0-3	0-6
		45-51	48-51	45-51
Third Year				
	Humanities Electives	9	9	9
Bi 11	Organismic Biology (3-3-3)	9	–	–
Bi/Ch 110 abc	Biochemistry (4-0-8)	12	12	12
Bi 122	Genetics (3-0-6)	–	9	–
Bi 123	Genetics Laboratory (0-4-2)	–	6	–
	Electives[1,2,3]	15-21	9-15	24-30
		45-51	45-51	45-51
Recommended Electives[2]				
Ch 21 abc	The Physical Description of Chemical Systems	9	9	9
Ch 24 ab	Introduction to Biophysical Chemistry	–	9	9
Fourth Year				
	Humanities Electives	9	9	9
Bi 150	Neurobiology (4-0-6)	10	–	–
	Electives[1,3]	26-32	36-42	36-42
		45-51	45-51	45-51

[1] *Electives must include sufficient units of work in biology to complete the graduation requirement for 143 units of work in biology.*

[2] *Ch 21 or the combination of Ch 21 a, Ch 24 ab is strongly recommended for students interested in postgraduate work in biology, as most graduate programs expect entering students to have taken a course in physical chemistry.*

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

Suggested Electives

Second Year

Second Term: Ch 4 a

Third Term: Bi 10, Ch 4 b

Third Year

First Term: Bi 22, Bi 23, Bi 135, Ch 21 a

Second Term: Bi 22, Bi 23, Bi 114, Bi 189, Ch 21 b, Ch 24 a, Ch 90

Third Term: Bi 22, Bi 23, Bi 115, Bi 137, Bi 156, Bi 157, Bi 158, Ch 21 c, Ch 24 b, Env 144

Fourth Year

In addition to those listed for the third year:

First Term: Bi 90 a, Bi 217, Ch 144 a, Ch 244 a

Second Term: Bi 90 b, Bi 125, Bi 127, Bi/Ch 132 a, Bi 152, Bi 154, Bi 161, Bi 162, Bi 220, Bi 225, Ch 144 b, Ch 244 b, CNS/Bi 186, Env 145 a, Env/Bi 166

Third Term: Bi 90 c, Bi/Ch 132 b, Bi 190, Bi 218, Bi 219, Bi 241, Env 145 b, Env/Bi 168, Ge 5

Chemical Engineering Option

Chemical engineering is based upon applications of chemistry, physics, mathematics, and, increasingly, biology and biochemistry. The chemical engineering curriculum includes the study of applied mathematics, material and energy balances, properties and physics of gases, liquids and solids, fluid mechanics, heat and mass transfer, thermodynamics, chemical kinetics and chemical reactor design, and the integrating subjects of process design, process control, and optimization. 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 manufacture of graphite, abrasives, and fuel cells; in the metallurgical industries; or in the biotechnology industry. Chemical engineering underlies most of the energy field, including efficient production and utilization of coal, petroleum, natural gas, oil shale, and geothermal deposits. 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 fundamental courses in mathematics, physics, and chemistry (Ma 1 abc, Ma 2 abc, Ph 1 abc, Ph 2 abc, Ch 1 abc, Ch 41 abc). Students interested in an introduction to the breadth of chemical engineering are encouraged to take ChE 10. The open-ended projects in ChE 10 also offer an opportunity to become acquainted with some of the faculty in chemical engineering.

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 of this option.

Option Requirements

1. Ch 41 abc, ChE 63 ab, AMa 95 abc, Ch 21 a and either Ph 2 c or Ch 21 c, ChE 101, ChE 103 abc, ChE 104, ChE 105, ChE 110 ab, ChE 126 a and ChE 126 b or ChE 90 ab, and either Ec 11, Ec 15, or BEM 100 a[1].
2. 18 units of chemistry electives[2].
3. 36 units of science and engineering electives.
4. Passing grades must be earned in a total of 486 units.

[1]*These 9 units partially satisfy the Institute requirements in humanities and social sciences.*
[2]*In addition to chemistry courses taught within the Division of Chemistry and Chemical Engineering, other courses such as Bi 110 and Env 142 may be used to satisfy this requirement.*

Typical Course Schedule

		Units per term		
Second Year		*1st*	*2nd*	*3rd*
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Sophomore Physics (4-0-5)	9	9	9
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
ChE 63 ab	Chemical Engineering Thermodynamics (3-0-6)	9	9	–
	Electives	9	9	18
		45	45	45
Third Year				
AMa 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
Ch 21 a	The Physical Description of Chemical Systems (3-0-6)	9	–	–
ChE 101	Chemical Reaction Engineering (3-0-6)	–	9	–
ChE 103 abc	Transport Phenomena (3-0-6)	9	9	9
ChE 104	Separation Processes (3-0-6)	–	–	9
	Electives	18	18	18
		48	48	48
Fourth Year				
ChE 105	Process Control (3-0-6)	9	–	–
ChE 110 ab	Optimal Design of Chemical Systems (3-0-9)	–	12	12
ChE 126 ab	Chemical Engineering Laboratory (1-6-2)	9	–	–
ChE 90 ab	Senior Thesis (0-4-5)	–	9	9
	Electives	18	18	18
		36	39	39

Chemistry Option

Study in the chemistry option leads, especially when followed by graduate work, to careers in teaching and research in colleges and universities, in research in 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 to systematize 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 with justification an alternate curriculum 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 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 abc, Ph 2 abc, and 108 units of humanities and/or social science as well as 9 units of PE.

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 15, and Bi 10.
3. A minimum of five terms of advanced chemistry electives from chemistry course offerings at the 100 and 200 level, including cross-listed offerings such as Bi/Ch 110 abc, 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		
Second Year		*1st*	*2nd*	*3rd*
Ch 41 abc	Chemistry of Covalent Compounds (3-0-6)	9	9	9
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ch 5 a	Advanced Techniques of Synthesis and Analysis (1-6-2)	9	–	–
	Electives	6-9	15-18	15-18
PE	Physical Education (0-3-0)	3	3	3
		45-48	45-48	45-48
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 core 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 5 ab[3], Ch 41 abc, Ma 2 abc, Ph 2 abc, HSS elective, other elective	Ch 14, Ch 21 abc, Ch elective(s)[4], Ch laboratory[5], Ch 80[6], Ch 90, HSS elective	Ch electives[4,5], Ch 80[6], HSS elective
Chemical Physics	Ch 21 abc[7], Ch 6 ab[7], Ch 14, Ma 2 abc, Ph 2 abc, HSS elective	Ch laboratory[8], Ch 41 abc[7], Ch elective(s)[9], Ch 80[6], Ch 90, HSS elective, AMa 95 ab	Ch 125 abc, Ch electives[8,9], Ch 80[6], HSS elective
Organic Chemistry	Ch 5 ab[3], Ch 41 abc, Ma 2 abc, Ph 2 abc, HSS elective, other elective	Ch 14, Ch 21 abc, Ch elective(s)[10], Ch laboratory[5], Ch 80[6], Ch 90, HSS elective	Ch electives[5,10], Ch 80[6], HSS elective
Chemical Biology	Ch 5 a[3], Ch 41 abc, Bi 1, Bi 9, Ma 2 abc, Ph 2 abc, HSS elective	Ch laboratory[11], Ch 14, Ch 21 a, Ch 24 ab (or Ch 21 bc), Ch 80[6] (or Bi 22), Ch 90, Bi/Ch 110 ab, Bi 10, HSS elective	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; if Ch 4 ab was not taken in the freshman year, it can be taken in the sophomore year, and Ch 5 ab deferred to the junior year.*

[4]*Ch 112, Ch 117, Ch 120 ab, Ch 122 ab, Ch 135 ab, Ch 144 ab, Ch 154, Ch 213 abc, Ch 241 ab, Ch 242 ab, Ch 247 ab.*

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

[6]*See "Research Opportunities for Undergraduates in Chemistry," which may be obtained from the Chairman of the Undergraduate Studies Committee.*

[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[3], Ch 15, Ch 118 ab, Bi 10.*

[9]*Ch 120 ab, Ch 127 ab, Ch 130 ab, Ch 135 ab, Ch 144 ab, ChE/Ch 164, ChE/Ch 165, Ph 106 abc, AMa 105 ab.*

[10]*Ch 112, Ch 120 ab, Ch 122 ab, Ch 135 ab, Ch 144 ab, Ch 146 ab, Ch 154, Ch 241 ab, Ch 242 ab, Ch 247 ab.*

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

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

Suggested Elective Courses for the Chemistry Option

1. *Chemical Engineering:* Chemical Engineering Systems (ChE 10), Chemical Engineering Thermodynamics (ChE 63), Undergraduate Research (ChE 80), Chemical Kinetics and Reactor Design (ChE 101), Transport Phenomena (ChE 103), Advanced Polymer Science (ChE 167), Polymer Science Laboratory (ChE 168), Introduction to Systems and Control (EE/ChE 170), Advanced Transport Phenomena (ChE 173).
2. *Biology:* Introduction to Molecular Biology (Bi 1), Cell Biology (Bi 9), Genetics (Bi 122).
3. *Engineering:* Introductory Methods of Applied Mathematics (AMa 95), Laboratory Research Methods in Engineering and Applied Science (E 5), Solid-State Electronics for Integrated Circuits (APh 3), Laboratory in Solid-State Electronics for Integrated Circuits (APh 9), Introduction to Linear Electronics (EE 5), Laboratory in Electronics (EE 90), Introduction to Computing (CS 10).
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), Introduction to Macroeconomics: Principles and Problems (Ec 15), Elementary French (L 102) or Elementary German (L 130) or Elementary Russian (L 141).
6. *Miscellaneous:* Introduction to Astronomy (Ay 1), Introductory Geology (Ge 1), Introduction to Geochemistry (Ge 130), Advanced Calculus (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; Econometrics, Ec 122; Business Cycles, Ec 161; and Monetary Theory, Ec 162. 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, Ec 122, Ec 161, and Ec 162.
2. Ma 112 a.
3. 54 additional units of advanced economics and social science courses. Students may take AMa 181 ab, BEM 103, or BEM 104 in partial fulfillment of this requirement.
4. 45 additional units of science, mathematics, and engineering courses. The requirement cannot be satisfied by courses listed as satisfying the in-

troductory laboratory requirement or by any course with a number less than 10.

5. Passing grades must be earned in a total of 486 units, including all courses used to satisfy the above requirements.

Typical Course Schedule

		Units per term		
Second Year		*1st*	*2nd*	*3rd*
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ec 11	Introduction to Economics (3-0-6)	9	–	–
PS/SS 12	Introduction to Political Science (3-0-6)	–	9	–
	Electives[1]	18	18	27
		45	45	45
Third Year				
Ec 121 ab	Theory of Value (3-0-6)	–	9	9
Ec 122	Econometrics (3-0-6)	–	9	–
Ec 161	Business Cycles (3-0-6)	–	9	–
Ec 162	Monetary Theory (3-0-6)	–	–	9
Ma 112 a	Statistics (3-0-6)	9	–	–
	Electives[1]	36	18	27
		45	45	45
Fourth Year				
Electives[1]		45	45	45

[1]*See requirements 4 and 5 above.*

Electrical Engineering Option

The electrical engineering option is designed to provide a broad exposure to the fundamentals of the electrical sciences while allowing some degree of specialization in a particular aspect of modern electrical engineering. Study in this option leads, especially when followed by graduate work, to research and development work in industry and government laboratories or to research and teaching in universities.

Students electing this option normally begin their work in their sophomore year with the theory and laboratory practice of analog and digital electronics in EE 14 abc, EE 90 ab, and CS/EE 4, although many may have already been introduced to the field through freshman electives. The junior-year program features basic courses in linear systems, EE 32 ab; communications, EE 160, or control, E 101; energy processing, EE 40; electromagnetics, EE 151; and solid-state devices, EE/APh 180. In the senior year, the student will ordinarily demonstrate his or her ability to formulate and carry out a research or development project, through either the senior thesis, EE 78 abc, or the senior project laboratory, EE 91 abc. The senior student may elect advanced courses to continue special interests begun in the required courses or in the electives taken in the sophomore and junior years; alternatively, a senior may select a broader range of topics from EE or other engineering or science courses.

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. AMa 95 abc.
3. EE 14 abc, EE 32 ab, EE 40, EE 151, EE 90 ab, EE 160 or E 101, EE/APh 180.
4. CS/EE 4 or CS 51.
5. EE 78 abc or two terms of EE 91 abc.
6. 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, E 101 and E/ChE 102 abc are acceptable.
7. Passing grades must be earned in a total of 486 units, including courses listed above.

Typical Course Schedule

		Units per term		
Second Year		*1st*	*2nd*	*3rd*
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
	Humanities Electives[1]	9	9	9
EE 14 abc	Introduction to Electronic Engineering (3-2-7)	12	12	12
	Electives	12	9	9
		51	48	48
Third Year				
AMa 95 abc	Introductory Methods of Applied Mathematics (4-0-8)	12	12	12
	Humanities Electives[1]	9	9	9
EE 32 ab	Introduction to Linear Systems (3-0-6)	12	9	–
EE 40	Fundamentals of Energy Processing Systems (3-0-6)	9	–	–
EE 151	Electromagnetic Engineering (3-2-7)	–	12	–
EE 160[2]	Communication System Fundamentals (3-0-6)	–	–	9
EE/APh 180	Solid-State Devices (3-0-6)	–	–	9
	Electives	9	9	9
		51	51	48

[1] *See Institute requirements for specific rules regarding humanities.*

[2] *See option requirement 3.*

Fourth Year				
	Humanities Electives[1]	9	9	9
E 10	Technical Seminar Presentations (1-0-1)	–	2	–
EE 91 ab[2]	Experimental Projects in Electronic Circuits	6	6	–
	Electives	27	27	36
		42	44	45

Suggested Electives

First-year students interested in electrical engineering should consider selecting one or two courses per term from APh 9, CS/EE 4, CS 10, CS/EE 11, E 5, Ph 3.

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.

	Second Year	*Third and Fourth Year*
Communications	Selected from APh/ME 17 abc, APh 23, APh 24, CS 51, CS 52, CS/EE 53, CS/EE 54	EE 112 ab, EE/Ma 126, EE/Ma 127 ab, EE 128, EE 162, EE 163 ab, EE 164, EE 165, EE/CS 183 abc, APh/EE 130, CNS/EE 124, APh/EE 131, APh/EE 132, Ma 112 a
Computer Engineering	CS 51, CS 52, CS/EE 53, CS/EE 54	CS 137, CS 139 ab, CS/EE 181 abc, and selections from EE 114 abc, EE/CS 183 abc, CNS/EE 124, CS 171 ab, CS/EE/Ma 129 abc
Control	APh/ME 17 abc	E 101, EE 117 ab, EE/ChE 170 ab, and selections from E/ChE 102 abc, EE/ChE 171, EE/ChE 172, EE 112 ab, EE 114 abc, EE 128, EE 162, EE 164
Electronic Circuits	APh/ME 17 abc	E 101, EE 112 ab, EE 114 abc, and selections from E/ChE 102 abc, EE/Mu 107 abc, EE 117 ab, EE 152, EE 153, EE 154, CS/EE 181 abc, CNS/CS/EE 182 abc, APh 181 ab

[1] *See Institute requirements for specific rules regarding humanities.*
[2] *See option requirement 5.*

Microwave Engineering	APh 23, APh 24, APh/ME 17 abc	EE 152, EE 153, EE 154, EE 157 abc, EE 158, APh 50 abc, APh/EE 130, APh/EE 131, APh 132, APh 181 ab
Optoelectronics	APh 23, APh 24, APh/ME 17 abc	APh/EE 130, APh/EE 131, APh/EE 132, APh 105 abc, APh 114 abc, APh/CNS/EE 133, APh 190 abc, EE 152
Solid-State Electronics	APh/ME 17 abc	APh 50 abc, APh 181 ab, and selections from APh 105 abc, APh 114 abc, 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. The student may undertake work in such diverse fields as environmental engineering science, solid-state physics, energy engineering and thermal science, the physics of fluids, applied mathematics, earthquake engineering, quantum electronics, aerodynamics, computer science, solid mechanics, materials science, soil mechanics, engineering science, elasticity and plasticity, plasma physics, the theory of waves and vibrations, mechanical systems, and engineering design. For those students who, in later life, hope to apply the science they learn to the useful and productive solution of the problems now confronting society, 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.

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 in their general fields of interest, 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 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.

Although a special electrical engineering option is available, students whose main interest is in electrical sciences may nevertheless choose the engineering and applied science option if they wish to pursue a broader course of studies.

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, CE, ChE, 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. AMa 95 abc or Ma 107 and either Ma 108 ab or Ma 109 ab. Neither sequence of courses may be taken pass/fail.
3. 126 additional units in courses in the following: Ae, AM, CE, ChE, 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 91 abc, Ae/APh 104 bc, CE 105, CE 111, CE 121, CE 180, CS/EE 53 and 54, CS 174 abc, CS/EE 181 abc, EE 90 abc, EE 91 abc, EE 153, Env 116, Env 143, JP 170, MS 90, ME 72, ME 96, ME 110.
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 in appropriate subjects.*
[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.*

Typical Course Schedule

	Units per term		
Second Year	*1st*	*2nd*	*3rd*
Ma 2 abc	9	9	9
Ph 2 abc	9	9	9
Humanities Electives	9	9	9
Electives	18	18	18
	45	45	45
Third Year			
AMa 95 abc or Ma 107 and either Ma 108 ab or Ma 109 ab	12	12	12
Humanities Electives	9	9	9
Electives	24	24	24
	45	45	45
Fourth Year			
E 10	–	2	–
Humanities Electives	9	9	9
Electives	33	33	33
	42	44	42

Notes:

- Suggested electives suitable for particular fields of interest follow.
- The programs formed with these suggested electives are only samples of typical programs and are *not* meant to represent special option requirements.
- These electives must be chosen so as to satisfy the laboratory requirements already given.

Suggested Electives

	First Year	*Second Year*	*Third Year*	*Fourth Year*
Aeronautics	One course per term selected from: APh/MS 4, ChE 10, E 5, CS/EE 4, CS 10, E 1	APh/ME 17 abc; one course per term selected from: MS 15 a, APh 23, APh 24, Ay 1	AM 35 abc, ME 19 abc; one course per term selected from: APh 50 abc, ChE 101, EE 90 abc, ME 22 abc, ME 71, ME 72, ME 73, MS 5 abc, E101	Ae/APh 101 abc, or CE/ME 101 abc, or Ae/AM 102 abc, and three courses per term selected from: Ae 103 abc, Ae/APh 104 abc, Ae/AM 108 abc, AMa 101 abc, AM 151 abc, E 102 abc, CE 111, ME 96, ME 115, JP 121 abc, APh 105 abc, APh 153 abc
Applied Mechanics	One course per term selected from: E 5, Ge 1, CS/EE 4, CS 10, CS/EE 11	One course per term selected from: APh/ME 17 abc, MS 15 abc, Ge 1, Bi 1, AM 35 abc	AM 35 abc or AM 151 abc, ME 19 abc, one course per term selected from: Ma 112 ab, EE 90 abc, APh 50 abc, MS 5 abc	AM 151 abc or Ae/AM 102 abc, AM 125 abc or AMa 101 abc; one or two courses per term selected from: ME 96, AM 135 abc, CE/ME 101 abc, Ph 106 abc, AMa 104, AMa 105
Civil Engineering: Structural and Soil Mechanics	One course per term selected from: ME 70, CS 10, E 5, Ge 1	One course per term selected from: APh/ME 17 abc, Ph 3, Ph 4, CS/EE 4, CS/EE 11, MS 15 a, AM 35 abc	CE 10 abc, ME 19 abc	Ae/AM 102 abc, CE 115 ab and CE 105, AM 151 abc, CE 180, 181, and 182 or CE 113 ab and CE 111, Env 112 abc or Env 146

Civil Engineering: Hydraulics and Water Resources	One course per term selected from: CS 10, E 5, Ge 1, Env 1	One course per term selected from: APh/ME 17 abc, Ph 3, Ph 4, CS/EE 4, CS/EE 11, MS 15 a, AM 35 abc	AM 102 abc, ME 19 abc, Ec 11, CE 111, ME 96	CE 10 abc, CE 115 ab and CE 150, CE 111 or ME 96, CE/ME 101 abc, CE 113 ab, Env 112 abc or Env 146, 147
Computer Science	CS 10, CS 12, CS/EE 4, CS/EE 11	CS 20 abc and either CS/Ma 6 abc or CS 51, CS 52, CS/EE 53	One or two courses per term selected from 100-level CS courses, including at least two of the full sequence of CS/EE/Ma 129 abc, CS 138 abc, CS 139 ab, CS/CNS 174 abc, CS/EE 181 abc	
Electrical Engineering	*See "Option Requirements" and "Suggested Electives" under: Electrical Engineering Option*			
Environmental Engineering Science[1]	Env 1; one course per term selected from: ChE 10, Bi 8, Bi 9, Ch 3 ab, E 5, Ge 1, CS 10	APh/ME 17 abc or ChE 63 abc; one course per term selected from: Env 144, Env 145 ab, Ch 14, Ch 15, Ch 41 abc, CS/EE 4, CS/EE 11, Ge 5, MS 15 a	ME 19 abc or ChE 103 abc, Env 142 ab and Env 143; one course per term selected from: Ch 21 abc, Ch 24 ab, Bi/Ch 110 abc	ChE/Env 157, 158, 159, plus Env 116 or Env 112 abc plus CE 111; one course per term selected from: Ge 152 abc, CE/ME 101 abc, CE 113 ab, Env 146, Env 147, Env 166, Env 168, AMa 101 abc, AMa 104, AMa 105
Materials Science	One course per term selected from: E 5, CS/EE 4, CS 10, ChE 10, APh/MS 4, APh 9	APh/ME 17 abc, MS 15 abc	Three courses selected from: AM 35 abc, MS 5 a, APh 50 abc, MS 105	MS 120, MS 121, APh/MS 122, MS 123

[1]*Electives in humanities and social sciences especially appropriate to this field are Ec 11, Ec 115, Ec 118.*

Mechanical Engineering: Fluids and Thermal Systems	One course per term selected from: E 1, E 5, CS 10, APh 9, CCO 1, Ph 20, APh/MS 4, Env 1*	Two terms either APh/ME 17 abc or ChE 63 abc, AM 35 abc (these courses strongly recommended). Env 1*, ME 71	ME 19 abc (two terms min.), ME 72, ME 22 abc*	ME 22* abc, ME 96, MS 15 abc, EE 32 ab, CE 111 *Advanced courses (1):* ME 118 abc, JP 121 abc
Mechanical Engineering: Systems and Design	One course per term selected from: E 1, E 5, CS 10, APh 9, CCO 1, Ph 20, APh/MS 4, Env 1	AM 35 abc, ME 71 (these courses strongly recommended)	ME 72, ME 73 ab, MS 15 abc, ME 19 abc (two terms min.), APh/ME 17 ab or ChE 63 ab	ME 19 abc, EE 32 ab, ME 96 *Advanced courses (1):* ME 115, ME 171 ab, Ae/ME 103 a, Ae 103 bc

**either year*

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), geophysics, 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 find further training at the graduate level necessary.

Attention is called to the fact that 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.

Option Requirements and Typical Course Schedules

Institute Requirements		*Year* 1	2	3	4
Ma 1 abc	Freshman Mathematics	27	–	–	–
Ph 1 abc	Freshman Physics	27	–	–	–
Ch 1 abc	General and Quantitative Chemistry	18	–	–	–
Ch 3 a	Experimental Chemical Science	6	–	–	–
	Freshman Laboratory	9	–	–	–
HSS	Humanities and Social Science Electives	27	27	27	27
PE 1 abc	Physical Education	9	–	–	–
	Freshman Electives	3	–	–	–
Ma 2 abc	Sophomore Mathematics	–	27	–	–
Ph 2 abc	Sophomore Physics	–	27	–	–
	Sophomore Science and Engineering Electives[1]	–	27	–	–
	Total required courses	126	108	27	27

[1]*These 27 units of sophomore electives should be used to broaden the students' backgrounds in science and engineering and to help them select an option. None of the introductory courses in the division, including Ge 1, Ge 4, and Ge 5, is specifically required of majors, but the election of one or more of these is highly recommended in the first or second year. The division recommends that an additional 9 units of physics, chemistry, and/or engineering laboratory courses be completed in the second year. The units may be selected from the first-year physics, chemistry, and engineering courses, e.g., Ph 5, Ph 6, Ph 7, and Ch 15.*

Division Requirements—All Options		*Year* 1	2	3	4
Ge 100	Geology Club Recommended	–	–	1	1
Ge 101	Intro to Geology	–	–	9	–
Ge 102	Intro to Geophysics	–	–	9	–
Ge 103	Intro to Planetary Science	–	–	–	9
Ge 105	The Geologic Record	–	–	9	–
Ge 107	Field Geology	–	–	9	–
Ge 109	Oral Presentation	–	–	–	2
	Total required courses	126	108	63	38
Geology Option Requirements					
Ge 106	Structural Geology			9	–
Ge 110	Sedimentary Geology			9	–
Ge 114	Mineralogy			12	–
Ge 115 ab	Petrology & Petrography			24	–
Ge 121 abc	Advanced Field Geology			–	36
	Math, Science & Eng. Electives[1]			–	54
	Total Required Courses			117	128

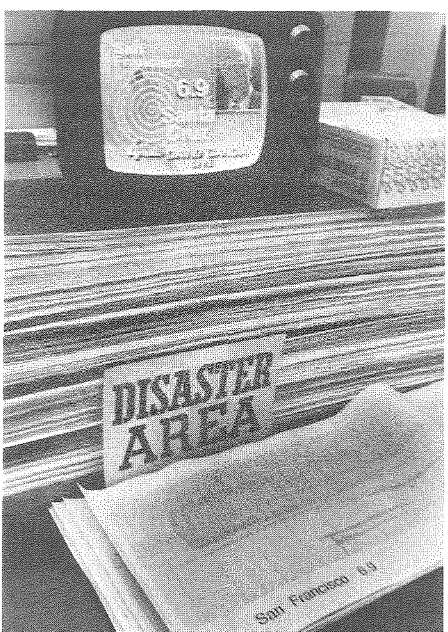
[1]*Ch 21, Ch 41, or Ph 106 recommended.*

The student should particularly note the opportunity for undergraduate research provided by Ge 40 and Ge 41.

Geochemistry Option Requirements		Year 3	Year 4
Ge 114	Mineralogy	12	–
Ge 115 ab	Petrology & Petrography	24	–
Ch 21 abc	The Physical Description of Chemical Systems[1]	27	–
Ch 14	Chemical Equilibrium and Analysis	–	6
Ch 15	Chemical Equilibrium and Analysis Laboratory	–	10
	Math, Science & Eng. Electives	–	54
	Total Required Courses	126	108

[1]*Ch 41 abc or other chemistry courses may be substituted with prior consent of adviser and option representative.*

Geophysics and Planetary Science Option Requirements		Year 3	Year 4
Ph 106 abc	Topics in Classical Physics	27	–
AMa 95 abc	Introductory Methods of Applied Mathematics	36	–
	Option Electives	–	54
	Math, Science & Eng. Electives	–	27
	Total required courses	126	119



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.
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 APh 3, APh/MS 4, Ay 1, Bi 2, CS/EE 4, EE 5, Env 1, or Ge 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 chairman and one other member must be on the professorial staff. The third member may be any qualified individual such as a postdoctoral fellow, graduate student, or faculty member of another institution.

2. The student must submit a written proposal to the Dean of Students, endorsed by the committee of three, describing his or her goals, reasons for applying, and plan of study for at least the next year. If persuaded that the proposal is sound and workable, the Dean endorses it and passes it on to the Curriculum Committee. This committee, in turn, reviews the proposal and, if it is acceptable, assumes responsibility for oversight of the program.

3. To implement the program, a written contract is now drawn up among 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 Chairman 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 choose from a wide range of courses that enable them to concentrate on either English or American literature. All majors are assigned an adviser who will help them select the courses best suited to their needs. It is recommended that literature majors take electives in such related fields as art history, languages, history, philosophy, and psychology. Majors would also be well advised to take one or more Lit 98 courses to consolidate their research interests. Majors preparing for graduate work should take more than the minimum requirements listed below. All literature courses must be taken for grades.

Option Requirements

1. 108 units in the Lit 100-180 group of courses. Within these 108 units, the following are required:
   a. 18 units (two terms) of Shakespeare, Lit 114 a and b.
   b. 27 units (three terms) selected from the following group of courses in pre-20th-century English literature: Lit 112 a or b, Lit 116, Lit 122 a or b.
   c. 27 units (three terms) selected from the following courses in American literature: Lit 131, Lit 132, Lit 138, Lit 145, and Lit 146 a.
2. L 102 abc or L 130 abc or L 141 abc or the equivalent.
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 APh 3, APh/MS 4, Ay 1, Bi 2, CS/EE 4, EE 5, Env 1, or Ge 1.
4. 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 expected 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, economics, computer science, business, or law. Students expecting to pursue a Ph.D. degree in mathematics should realize that many mathematics departments require a reading knowledge of one or two foreign languages.

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. Each term during their junior and senior years, students normally take 18 units of courses in mathematics or applied mathematics, including the required courses Ma 107, 108 ab, and 109 ab. Any course listed under applied mathematics is regarded as an elective in mathematics and not as an elective in science, engineering, or humanities. Sophomores who have not taken Ma 5 must take this course 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 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 107, Ma 108 ab, Ma 109 ab.
2. Two quarters (18 units) of a single course, chosen from the following: Ma 110, Ma 116, Ma/CS 117, Ma 120, Ma 121, Ma 122, Ma/EE 126-127, Ma/CS/EE 129, Ma 142, Ma 144, Ma 147, Ma 151, Ma 160.
3. 27 additional units in Ma or AMa.
4. 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 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
Ma 5 abc	Introduction to Abstract Algebra (3-0-6)	9	9	9
	Electives in Science, Engineering, or Humanities	9	9	9
	Humanities Electives	9	9	9
		45	45	45
Third Year				
Ma 107	Introduction to Analysis (4-0-5)	9	0	0
Ma 108 ab	Classical Analysis (3-0-6)	0	9	9
	Selected course in Mathematics, minimum	9	9	9
	Humanities Electives	18	18	18
	Electives in Science, Engineering, or Humanities	9	9	9
		45	45	45
Fourth Year				
Ma 109 ab	Geometric Analysis (3-0-6)	0	9	9
	Selected course in Mathematics	9	9	9
	Humanities Electives	18	18	18
	Electives in Mathematics, Science, Engineering, or Humanities	27	18	18
		54	54	54

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 two years 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

Laboratory Courses:

1. Ph 3.
2. One of the following:[1] Ph 5, Ph 6 or APh 24.
3. Ph 7.

The above three requirements must be completed by the end of the second year. In planning a program, note that Ph 5, 6, and 7 are each offered only once per year, in the first, second, and third terms, respectively.

4. 18 units of Ph 77, APh 77, or Ph 78 in any combination.

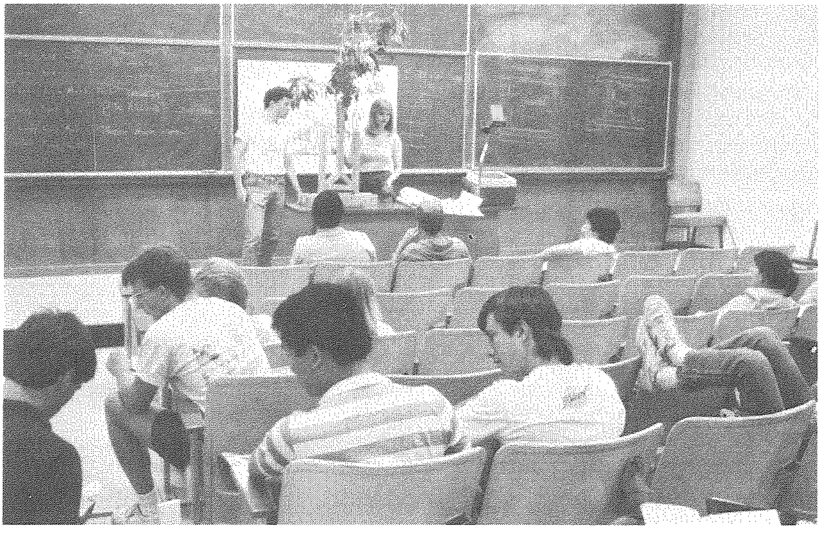
Fundamental Physics:

5. Ph 106.
6. Ph 98 or 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 AMa 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. Other courses in other departments with substantial physics content may be approved by the Physics Undergraduate Committee in individual cases. 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 AMa.
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

	Units per term		
	1st	2nd	3rd
Second Year			
Ph 2 or Ph 12	9	9	9
Ma 2	9	9	9
Humanities	9	9	9
Physics Laboratory	0	9	9
Electives	12	9	9
	39	45	45
Third Year			
Ph 106	9	9	9
Ph 98[1]	9	9	9
AMa 95 or Ma 108	12	12	12
Humanities	9	9	9
Electives	9	9	9
	48	48	48
Fourth Year			
Ph 77	9	9	0
Advanced Physics Electives	18	18	18
Electives	9	9	18
Humanities	9	9	9
	45	45	45

[1] *Students who took Ph 2 should consult their adviser as to whether Ph 125 in their senior year might be more appropriate.*

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/SS 12, Ec 121 a, Ma 112 a, Ec 122, PS/SS 122.
2. One of the following: An 22, An 101, Psy 10, or Psy 12.
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, political science, psychology, and social science.
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/SS 12	Introduction to Political Science (3-0-6)	–	9	–
Ma 2 abc	Sophomore Mathematics (4-0-5)	9	9	9
Ph 2 abc	Waves, Quantum Mechanics, and Statistical Physics (4-0-5)	9	9	9
	Electives	18	18	27
		45	45	45
Third Year				
Ma 112 a	Statistics (3-0-6)	9	–	–
Ec 121 a	Theory of Value (3-0-6)	9	–	–
Ec 122	Econometrics (3-0-6)	–	9	–
PS/SS 122	Noncooperative Games in Social Science (3-0-6)	–	–	9
An 101 a or	Selected Topics in Anthropology (3-0-6)	9	–	–
An 22 or	Introduction to the Anthropology of Development (3-0-6)	–	9	–
Psy 10 or	Introduction to Psychological Development	–	–	9
Psy 12	Introduction to Abnormal Psychology	–	–	–
	Electives	18	27	27
		45	45	45
Fourth Year				
Electives[1]		45	45	45
		45	45	45

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

Section Four

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 1990–91 are as follows:

Aeronautics	Prof. W. G. Knauss
Applied Mathematics	Prof. G. B. Whitham
Applied Mechanics	Prof. E. E. Zukoski
Applied Physics	Prof. P. M. Bellan
Astronomy	Prof. K. Libbrecht
Biology	Prof. S. D. Emr
Chemical Engineering	Prof. G. Gavalas
Chemistry	Prof. D. Dougherty
Civil Engineering	Prof. J. L. Beck

Computation and Neural Systems	Prof. D. Van Essen
Computer Science	Prof. K. M. Chandy
Electrical Engineering	Prof. D. B. Rutledge
Engineering Science	Prof. T. Y. Wu
Environmental Engineering Science	Prof. N. Brooks
Geological and Planetary Sciences	Prof. K. E. Sieh
Materials Science	Prof. B. Fultz
Mathematics	Prof. D. Ramakrishnan
Mechanical Engineering	Prof. E. E. Zukoski
Physics	Prof. S. C. Frautschi
Social Science	Prof. L. E. Davis

GENERAL REGULATIONS

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. No application fee is required. 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. 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 by two or more divisions or interdisciplinary programs.

To be admitted to graduate standing an applicant must in general have received a bachelor's degree representing the completion of an undergraduate course in science or engineering equivalent to one of the options offered by the Institute. He or she must, moreover, have attained such a scholastic record and present such recommendations as to indicate fitness to pursue, with distinction, advanced study and research. Admission sometimes may have to be refused solely on the basis of limited facilities in the option concerned.

Required Tests

The Graduate Record Examination is strongly recommended by all options and required by some for all applicants.

Students from non-English-speaking countries are expected to read, write, and speak English and comprehend the spoken language. Applicants whose first or native language is not English are required to take the Test of English as a Foreign Language (TOEFL) as part of their application procedure. This test is given at centers throughout the world on several dates each year. The testing schedule and registration information may be obtained by writing to TOEFL, Educational Testing Service, Princeton, NJ 08540. Results of the test should be sent to the Graduate Office. Special no-credit classes in English are provided for those students who need to improve their command of oral English. Information regarding these classes can be obtained from the Graduate Office. It is strongly recommended that students who achieve a low TOEFL score or who have little opportunity to communicate in English make arrangements for intensive work during the summer preceding their registration. The Graduate Office can provide information on schools that provide such intensive study.

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 leave of absence from, an advanced degree program at another institution and who need to make use of resources available at Caltech. Admission to such status requires application 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 shortened in 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. Mail registration is provided for graduate students during a two-week period near the end of the previous quarter. A late registration fee of $50.00 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 in case he or she feels that the progress of 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.

A graduate student who is registered for 36 or more units is classified as a full-time student. A graduate student who registers for less than 36 units, or who undertakes activities related to the Institute (class, research, and teaching assistantship units) aggregating more than 62 hours per week 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.

Academic Year and Summer Registration
Most courses are taught during the three 11-week quarters that make up the academic year. However, predoctoral students are strongly encouraged to continue their research throughout the year. 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.

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 as well as in the regular terms.

Leave of Absence
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 leave. A leave of absence for medical or other reasons may be approved for up to one year at a time. An approved leave of absence indicates that the student can return to the option at the end of the leave. Financial aid awarded by the Institute may not be deferred from

the term for which it was originally offered and must be requested again for the term of reenrollment.

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 leave of absence, or detached or reduced duty status, may be obtained from the Graduate Office and must carry the recommendations of the student's option representative and, where appropriate, the thesis adviser before submission to the Dean of Graduate Studies. 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 leave of absence 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.

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 are subject to the following rules:

Degree Programs

- Applicants for the part-time program must submit a regular application form.
- Any research work done for academic credit shall be supervised by a Caltech faculty member.
- 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. They may not commit themselves to work for more than 20 hours per week for the sponsoring organization.
- Part-time studies in the program will be limited to the first two years of academic residence for each student. Beyond the initial period, students continuing their graduate work must do so on a full-time basis.
- Any option at the Institute retains the right to not participate in the program or to accept it under more stringent conditions.

Nondegree Programs

Caltech employees, both campus and JPL, are eligible to apply to take one or more graduate courses for credit. Participants in this program will not be considered to be working toward a Caltech degree, in contrast to the part-time program for graduate degrees described above, and courses taken under this program cannot be used to fulfill the requirements for a Caltech degree.

At least one month prior to the start of the term, the employee should have an initial discussion with the option representative of the option in which the course is to be taken. Application should be made to the Graduate Office by completing the special form provided for this purpose, and providing a transcript of academic work and one letter of recommendation. The employee must meet the prerequisites for the course, and must obtain the written permission of the instructor. Individual options may require further information such as GRE scores. The decision on admission to take each course will be made by the course instructor and the option representative, with final approval by the Dean of Graduate Studies. Taking an additional course at a later time will require full reapplication. It is the employee's responsibility to arrange a revised work schedule with the appropriate supervisor. Approval of the employee's division is required.

Part-time nondegree students are subject to the Honor System (see page 26) 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

- Any student who desires to take advantage of the unique opportunities available at the special laboratories, e.g., JPL or EQL, 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 laboratories commit support for the duration of the thesis research, and provided that all Caltech graduate thesis research carried out at the special laboratories 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 of 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.
- Special laboratories' support of Caltech students doing thesis research at the special laboratories should be provided, if possible, through a campus graduate research assistantship (GRA) under a suitable work order. In this way a student would be eligible for a tuition award on the same basis as a campus thesis student.
- Employment by the special laboratories 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.

DEGREE REGULATIONS

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.

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. 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 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 candidacy form, the student must submit a proposed plan of study, which must have the approval of his or her option. 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 chairman 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 probably can be finished at the expected time.

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 chairman 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 language.

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 any option. Completion of a minor program of study is recognized on the Ph.D. diploma by the statement, " . . . and by additional studies 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 (15 terms) of graduate residence, nor more than 18 terms for full- or part-time academic work, 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.

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 leaves of absence. Registration is required for the quarter in which the thesis defense is undertaken, with the exception of the first week of the quarter.

Admission to Candidacy. On recommendation of the chairman 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 the several options concerned by written or oral examination or otherwise shown that he or she has a comprehensive grasp of the major and minor subjects and of subjects fundamental to them; has fulfilled any necessary language requirements; and has shown ability in carrying on research in a subject approved by the chairman 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.

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 Chairman 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. A student may petition the Dean of Graduate Studies for registration for 10 units and for minimum tuition charges if the student supplies a copy of the thesis, schedules the examination, and submits the necessary petitions for the Ph.D. examination and for the 10 units registration prior to 5:00 p.m. on the third Friday of the term in which the examination will be taken. A student need not register and will not be charged tuition for the term in which the thesis examination is taken, provided the examination is taken and passed before 5:00 p.m. on the first Friday of that term. In addition, all necessary procedures must be followed, including adhering to the deadline dates mentioned above and maintaining continuity of registration.

The last date for submission of the final, corrected thesis to the Dean of Graduate Studies is May 1 if the candidate defended his or her thesis during the previous summer, 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 chairman 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 $13,300 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 should 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 $123 a unit for fewer than 36 units, with a minimum of $1,230 a term. This tuition credit will only be made for reduced units as of the published Add Day of each term. However, if tuition credit has been applied to students' accounts for reduced units, any subsequent increase in tuition units will result in the appropriate tuition charge for the increased number of units retroactive to the beginning of the academic term. Additional tuition will be charged to students registering for special courses that are not part of the normal educational facilities of the Institute.

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 $25 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 Office of Student Accounts.

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 1990–91

General:	
General Deposit	$ 25.00[1]
Tuition	13,300.00
Graduate Student Council Dues	24.00[2]
	$13,349.00
Other:	
Books and Supplies (approx.)	$750.00

Graduate House Living Expenses

Room—$275.00 to $360.00 (for single students) per month[3]
$605.00 to $720.00 (for married students) per month[3]
(Room rates are subject to change.)

Meals—Available at Chandler Dining Hall or the Athenaeum (members only)

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

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

[3] *Room rent is billed at the end of each month and is payable upon receipt of the monthly statement.*

The following is a list of graduate fees at the California Institute of Technology for the Academic Year 1990–91, together with the dates on which these charges are due. Fees are subject to change at the discretion of the Institute.

	First Term	*Fee*
October 1, 1990	General Deposit	$ 25.00
	Tuition	4,434.00
	Graduate Student Council Dues	8.00
	Second Term	
January 7, 1991	Tuition	$4,433.00
	Graduate Student Council Dues	8.00
	Third Term	
April 1, 1991	Tuition	$4,433.00
	Graduate Student Council Dues	8.00

Tuition fees for fewer than normal number of units:

36 units	Full Tuition
Per unit per term	$ 123.00
Minimum per term	1,230.00
Audit Fee, $123.00 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.

ASCIT Dues. Graduate students are eligible for membership in the Associated Students of the California Institute of Technology, Inc., or ASCIT, pursuant to by-laws thereof. Dues are $60 annually.

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.

Refunds. Students withdrawing from the Institute during the first three weeks of a term are entitled to a partial refund of tuition based on the period of attendance. The schedule for the specific percentage of tuition to be refunded for specific days of attendance appears in Section 3. The days in attendance are the number of days counted from the first day of the term to the date that the petition for *withdrawal* or *leave of absence* is approved by the Dean of Graduate Studies. Approval is required each term from the Dean of Graduate Studies for reduction of units (to fewer than 36).

Honor System Matters. Monies owed to the Institute resulting from a Graduate Review Board decision may be collected through Student Accounts, at the request of the Dean of Graduate Studies.

Housing Facilities. The Institute has three dormitories on campus providing single rooms for 119 graduate students. In September 1984, the Institute completed construction of an apartment complex, Catalina I, that provides an additional 152 single rooms in four-bedroom furnished units. Catalina II, completed in September 1986, has 156 single rooms in two-bedroom furnished units. Catalina III, completed in September 1988, has 54 single rooms in two-bedroom furnished units, and 30 one-bedroom furnished units. These apartments are also available to married students with families.

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. The deposit will be refunded if there is no delinquent rent or damages. Complete information and reservations can be obtained by writing to the Housing Office, Mail Code 1-56, 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 Housing Office, Mail Code 1-56, 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 for use upon arrival at Caltech. Students preferring to live in non-Institute housing typically pay approximately $350–$450 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 the Institute, 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.

Health Services. Health services available to graduate students are explained in Section 1.

The International Desk. The International Desk is maintained to help foreign students and visiting scholars with nonacademic problems. They will find the services of the desk very helpful, particularly when they first arrive on campus. The International Desk operates under the advice of the Faculty Committee on Foreign Students and Scholars.

FINANCIAL ASSISTANCE

Caltech offers in each of its divisions 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 that applicant may be at a disadvantage in the allocation of financial assistance. Appointments to fellowships, scholarships, and assistantships are for one year only; and 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 any financial aid from other sources to the Dean of Graduate Studies. Students may 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.

Loans are available to graduate students who need such aid to continue their education. Application should be made to the Graduate Office.

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. Research assistantships are up to 20 hours per week during the academic year and may be greater during the summer. Combined teaching and research assistantships are common. Assistantships normally permit carrying a full graduate residence schedule also.

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, 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 assistantships.

Work-Study Programs

Limited opportunities are available for work-study programs in certain areas of interest. At the present time the sponsors of such programs are the Hughes Aircraft Company (Scientific Education Office, World Way, P.O. Box 90515, Los Angeles, CA 90009) and the Jet Propulsion Laboratory of the California Institute of Technology. Potential students considering participation in the Hughes program may make inquiry to the address above when applying for graduate study. Those wishing to be considered for the JPL program should consult JPL and their option representative after their admission. In general, such programs require some part-time employment during the academic year, as well as full-time work during the summer.

Loans

There are three sources of loans available to graduate students: federal loans under the Perkins Loan (Carl D. Perkins National Direct Student Loan) program; loans under the Stafford Loan (previously Guaranteed Student Loan) program; and loans from special funds of the California Institute of Technology. The amount of loans available from the programs of the federal government is limited by the appropriate government regulations. Perkins Loan borrowers are subject to the same repayment terms and qualification requirements as those outlined for undergraduate students on page 97. Caltech loan funds are also listed on page 97. Repayment terms, including interest rates, may be obtained from the Office of Student Accounts.

PRIZES

William F. Ballhaus Prize

A prize of $750 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 U.S. 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.

W. P. Carey & Co., Inc., Prizes in Applied Mathematics

Prizes of up to $500 will be awarded by a faculty committee in applied mathematics for outstanding doctoral dissertations. 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 $200 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 of $1,500 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 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 chairman of the Division of Engineering and Applied Science names the student to receive the award.

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.

Ernest E. Sechler Memorial Award in Aeronautics

An award of $500 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 $350 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.

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 fracture, aeronautical engineering and propulsion, and aero-acoustics.

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.

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. Of the 135 units of graduate work required by Institute regulations, 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

In addition, three units of Ae 150 are required. 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.

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 135 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, Ae/AM 209, or JP 290; 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, 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 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 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).

Candidacy. To be recommended for candidacy for the Ph.D. in aeronautics, the applicant must have satisfactorily completed at least 135 units of graduate work equivalent to the above Master of Science program and, in addition, must pass one of the following, or its equivalent, with a grade of C or better:

AMa 101 abc .... Methods of Applied 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, excluding research and seminars
- at least 54 units of courses outside of the applicant's chosen discipline, approved by the aeronautics faculty, or a subject minor.

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 at least one year before the degree is expected to be conferred. 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. By the beginning of the third term of the year in which the degree is to be conferred, a candidate for the degree of Doctor of Philosophy must deliver rough drafts of the thesis to the supervising committee. Not less than two weeks after the submission of the thesis rough drafts, the candidate is expected to give a seminar covering the results of his or her research, and this seminar will be followed by a thesis examination by the supervising committee. The seminar should be given as early as possible, but not later than two months before the degree is to be conferred.

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 Mathematics

Aims and Scope of Graduate Study in Applied Mathematics
A program for graduate study in applied mathematics leads to the Ph.D. degree and requires four or five years. This program is aimed at those students with a background in mathematics, physics, or engineering who wish to obtain a thorough training and to develop their research ability in applied mathematics.

Reflecting the interdisciplinary nature of the program, several different groups in addition to the applied mathematics faculty contribute to the teaching and supervision of research. Students in applied mathematics are expected to combine their basic mathematical studies with deep involvement in some field of application. In accordance with this, basic general courses are listed specifically under applied mathematics; these are to be supplemented, according to the student's interest, from the whole range of Institute courses in specific areas of physics, engineering, etc.

There is an applied mathematics colloquium in which visitors, faculty, and students 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.

Categories of Courses
Courses that are expected to form a large part of the student's program are divided by the applied mathematics faculty into three categories as follows:

Group A. Courses in mathematics and mathematical methods. Examples of these include AMa 101, AMa 104, AMa 105, AMa 156, AMa 204, Ma 107, Ma 109 ab, Ma 121, Ma 142, Ma 144, Ma 147, Ma 151.

Group B. Courses of a general nature in which common mathematical concepts and techniques are applied to problems occurring in various scientific disciplines. Examples of these include: AMa 151, AMa 152, AMa 153, AMa 181, AMa 220, AMa 251, AMa 261.

Group C. Courses dealing with special topics in the sciences. A complete list cannot be given here, but examples are courses in elasticity, fluid mechanics, dynamics, quantum mechanics, electromagnetism, communication theory, and computer science.

Master's Degree in Applied 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 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 during the first term of the second graduate year. It is based upon one year's work in courses of the type described in group A above, and upon one year's work in courses of the type described in groups B and C. The examination will also cover any independent study carried out by the student during his or her first graduate year.

Further Requirements. In order to be recommended for the Ph.D. in applied mathematics, the student must do satisfactory work in a program containing at least 45 units of work in courses of the type indicated in group A, and at least 45 units of courses chosen from groups B and C. This is intended to prevent undue specialization in either the more mathematical or the more engineering types of courses.

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 Mathematics

A subject minor is not required for the Ph.D. degree in applied mathematics. However, graduate students in other options may pursue a subject minor in applied mathematics. The group of courses must differ markedly from the major subject of study and include 54 units of advanced courses in applied mathematics, excluding AMa 101, 104, 105. The student must pass an oral examination that is separate from the examination in the student's major.

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 methematics *and* computer science in these same subjects. These subjects include *at minimum* mathematical and numerical methods, algorithms, and advanced programming, and may also include other areas of particular relevance to a student's research area, such as specialized mathematical methods, computer graphics, simulation, or computer-aided design.

Each proposed program must be approved by a faculty committee composed of the option representatives of applied mathematics and computer science, and one faculty member appointed by the chairman 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 course work totaling at least 135 units. The program must include E 150 abc and one course from among the following: AM 114 abc, AM 125 abc, AMa 101 abc, or either of the combinations Ma 107, Ma 108 ab, or Ma 107, Ma 109 ab. Note that neither AM 114 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 (numbers 100 and above) must be selected from courses in AM, AMa, Ae, JP, CE, and ME with the approval of the student's adviser and the faculty in applied mechanics. Students are encouraged to consider a humanities elective as part of their free electives.

Students admitted for study toward a master's degree but interested in pursuing subsequent study toward a Ph.D. degree in applied mechanics should also read the following section concerning the Ph.D. degree.

Degree of Doctor of Philosophy in Applied Mechanics

The degree of Doctor of Philosophy in applied mechanics ordinarily involves a second year of graduate work in advanced courses and research, plus at least one additional year on a comprehensive thesis research project. Such study and research programs are individually planned to fit the interests and background of the student.

Counseling. 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 chairman and interim adviser until this responsibility is assumed by the dissertation supervisor.

In addition, a special joint faculty committee is appointed annually by the faculties in applied mechanics, civil engineering, and mechanical engineering, which meets with first-year graduate students aiming toward the doctoral degree, in order to provide further perspective on graduate study and research.

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 referred to above, is confined to elementary but basic topics.

Admission to Candidacy for the Ph.D. in Applied Mechanics. To be recommended for candidacy for the Ph.D. degree in applied mechanics, the student must, in addition to meeting the general Institute requirements:

- complete 12 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 thereof 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 advanced course in mathematics or applied mathematics such as AM 125 abc, Ph 129 abc, or AMa 101 abc, 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 an oral examination on the major subject, and, if the student has a minor, examination on the subject of that program may be included at the request of the discipline offering the minor.

Language Requirements. The student is encouraged to discuss with his or her adviser the desirability of taking foreign languages, which may be included in a minor with proper approvals. 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 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 advanced work. The student shall 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, Ch 125 or Ph 125, APh 105, Ae/APh 101, and APh 156.

Topics in Applied Physics, APh 110 abc, 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/EE 130, APh/EE 131, APh/EE 132, APh 156, APh 181, APh 190, APh 200, Ph 125, Ph 129, AMa 101, AMa 104, AMa 105, AM 135, ChE 103, ChE 165, Ch 120, Ch 125, Ge 104, Ge 154, Ge 166. As a result of consultation with his or her adviser, a student may be required to take AM 113 abc, 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: Ph 125 or Ch 125
    3. Mathematical Methods
       course level: AMa 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

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, should he or she supply evidence of having done equivalent course work elsewhere, the student will be permitted to 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 student's proposed thesis research adviser, normally the projected research topic. 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 181, APh 214
Group C: APh/EE 130, APh/EE 131, APh/EE 132, 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 200) 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, Ay 127, and Ay 128. 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 two first-term courses are required of all students: Ay 121 and Ay 122; in addition, 36 units chosen from Ay 123, Ay 124, Ay 125, Ay 126, Ay 127, and Ay 128 are required for candidacy. The student should take the 6 courses necessary for this 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, and Ph 129. Students in radio astronomy may substitute an advanced course in electrical engineering or applied mechanics for up to 9 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.

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 strongly that knowledge of foreign languages is useful in astronomy, 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 and Ay 122, plus four of the following: Ay 123, Ay 124, Ay 125, Ay 126, Ay 127, and Ay 128;
- pass a written examination (see below);
- pass an oral examination (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 Institute of Washington.

The written examination will be given in October of the second year. It will cover the material from the required astronomy courses and will consist of two three-hour papers. An oral 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 in consultation with the student's adviser and approved by the option representative. Special permission will be required for further registration if the candidacy course requirements and the written and the oral examinations are not satisfactorily completed by the end of the third year of graduate work.

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.

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.

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, such as completion of an advanced degree at another institution, which 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, 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.

Advisory Committees

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 three or four faculty members, including a student's current research supervisor and at least one member of the Graduate Admissions Committee, who will serve as chairman of the advisory committee. 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; again in the third term of the first year of study to discuss progress and subsequent plans; and at other times when problems arise or advice is needed.

Teaching Requirements for Graduate Students

All students must acquire teaching experience.

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.

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:

- 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.

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 candidacy examination in the major subject and one or two minor subjects from the list of major subjects of specialization.

Thesis Committee. Before admission to candidacy, a thesis advisory committee is appointed for each student by the chairman of the division upon consultation with the student and the major professor. This committee will consist of the student's major professor as chairman 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 ability to carry out independent research, and at 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 chairman, to allow as much time as necessary for such matters as publication 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 regulation 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.

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, 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 the principles of mathematics, the physical and biological sciences, and engineering to the fundamental understanding of systems involving chemical reactions and transport phenomena and to the development of new processes and materials.

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 division may prescribe additional work in these subjects before recommending him or her as a candidate.

Master's Degree in Chemical Engineering
The master's degree is intended for students who plan to pursue careers in design, process engineering, development, or management. The degree is normally obtained in 18 months.

Course Requirements. At least 135 units of course work must be completed in order to satisfy the Institute requirements. Of that 135, the following courses are required: ChE 151 abc, ChE 165, 18 additional units of advanced courses in chemical engineering, 27 units of science or engineering electives, and 27 units of general electives. Finally, the M.S. requirements include at least 18 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 three members of the faculty. A copy of each approved M.S. report will be kept in the chemical engineering library.

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, although Ph.D. graduates are also well qualified for the areas listed for the master's degree. 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 of a research project and to its initiation. 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 judge the level of preparation needed, with respect to that expected at the Ph.D. level, in the areas of kinetics, thermodynamics, and transport phenomena. The chief intention of these consultations is to provide a guide 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.

Course Requirements. Students are required to take ChE 151 abc, ChE 164, ChE 165, and one ChE 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 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 AM 113, AM 114, and research in another option. The requirements for a subject minor in any option are listed in this catalog. A grade of C or better is required in any course.

Candidacy Requirements. To be recommended for candidacy the student must demonstrate proficiency at the graduate level in chemical engineering. This is done by way of chemical engineering courses; an oral subject examination, which is to be taken at the beginning of the second term of the student's first year of graduate residence at the Institute; and a written progress report on his or her research, to be submitted before the end of the first term of the student's second year of graduate residence. The oral examination will cover thermodynamics, applied chemical kinetics and design, and transport phenomena, with emphasis at the discretion of the committee. Approval of the research report constitutes the final step for admission to candidacy. A student who fails to satisfy the division's candidacy requirements by the end of the third term of his or her second year of graduate residence at the Institute will not be allowed to register in a subsequent academic year except by special permission of the division.

Thesis and Final Examination. See page 149 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 be concerned with the candidate's oral presentation and defense of a brief résumé of his or her research.

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 abc, 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.

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; they are not confined to a biochemical or physical or organic laboratory. A thesis that involves more than one adviser is not uncommon, and interdisciplinary programs with biology, physics, and geology 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 chemical biology. Graduate students are also encouraged to attend seminars in other divisions.

Placement Examination
During the week preceding registration for the first term of graduate study, students admitted to work for advanced degrees will be required to take written placement examinations in the fields of inorganic, organic, and physical chemistry and chemical equilibrium. In general, they are designed to test whether students possess an understanding of general principles and a power to apply these to specific problems. Students are expected to demonstrate a proficiency in the above subjects not less than that acquired by advanced undergraduates.

If a student fails to show satisfactory performance in any area of the placement examination, he or she will be required to complete satisfactorily a prescribed course, or courses, in order to correct the deficiency. All placement examination requirements must be satisfied before a student can be admitted to candidacy.

Course Program
For an advanced degree, no graduate courses in the principal area of research are required. Course work is involved in satisfying the minor requirement, as described below. Students should plan a program of advanced courses in consultation, at first with a representative of the Chemistry Graduate Study Committee, and later with their research adviser.

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 chem-

ical 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 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 ten days 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 chairman of the Chemistry Graduate Study Committee.

Degree of Doctor of Philosophy in Chemistry

Candidacy. There is no formal course work required in the *major* field of interest (for minor requirements, see below). However, 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). At this 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 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.

The Minor. In order to provide breadth in a student's graduate experience, he or she is required either to (a) complete a subject minor in another option (the requirements being set by that option) or (b) complete an approved program of course work outside the principal area of research. This program consists of at least 36 units of course work (the equivalent of approximately four standard one-term courses) outside the scientific area in which the dissertation research is performed. These courses may be either inside or outside the chemistry option. Courses for the minor shall be taken on a letter grade basis unless the course is offered with only a pass/fail option. A grade of C or better is required for credit toward the minor. The adviser has the responsibility of determining which courses fulfill the requirement in each particular case, subject to final approval by the Chemistry Graduate Study Committee.

Length of Graduate Residence. Any graduate student who anticipates a need to register for a sixteenth academic term must request a meeting of his or her candidacy 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 meeting must be held before the end of the third quarter of the fifth academic year of the student's studies. A recommendation from the candidacy committee must be submitted for approval to the chairman of the Chemistry Graduate Study Committee, and, in cases where financial support is an issue, to the Executive Officer or Division Chairman, 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 propositions are required. No more than *one* of these may be a carry-over 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. examining committee. This examination on the propositions must be held not less than ten 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 examining 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 an 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 applied 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 is required. The program must include three units of CE 130 abc and 108 units (minimum) of graduate level courses (numbers 100 and above) from at least three of the five general subject areas of structures and solid mechanics, soil mechanics, hydraulics and water resources, environmental engineering science, and mathematics. Students who have not had AMa 95 abc or its equivalent will be required to include either AM 113 abc or AM 114 abc in their program. The faculty encourages students to take 27 units in the humanities and social sciences.

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
Upon admission to work toward the Ph.D. degree in civil engineering, a counseling committee of three members of the faculty is appointed to advise the student on his or her program. One member of the committee who is most closely related to the student's field of interest serves as interim chairman and adviser. The student's thesis adviser is chosen by the student and the advisory committee at a later time, when the student's research interests are more clearly defined.

In addition, a special joint faculty committee, appointed annually by the faculties in applied mechanics, civil engineering, and mechanical engineering, meets with first-year graduate students aiming at the doctoral degree, in order to provide further perspective on graduate study and research.

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 referred to above, is confined to elementary but basic topics.

Major Subjects of Specialization. A student may pursue major work leading to the doctor's degree in civil engineering in any of the following disciplines: structural engineering and applied mechanics, earthquake engineering, soil mechanics, hydraulics, coastal engineering, and environmental engineering. Other disciplines may be selected with approval of the civil engineering faculty.

Course Requirements. A student must 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 subjects, other than the required mathematics, not closely related to their thesis research. If a student elects to take a subject minor, the units so taken may be included in the total 108, and shall be subject to the approval of the faculty in civil engineering.

Admission to Candidacy. To be recommended to candidacy for the Ph.D. degree in civil engineering the student must, in addition to meeting the general Institute requirements:

- complete a program of advanced courses as arranged in consultation with his or her advisory committee, and approved by the faculty in civil engineering;
- pass at least 27 units of course work in advanced mathematics, such as AM 125, AMa 101, Ph 129, or a satisfactory substitute. For a student whose program is more closely related to the sciences of biology or chemistry than physics, AMa 104 and AMa 105 (or AMa 104 and AMa 181 ab) will be an acceptable substitute for the mathematics requirement;
- 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.

The oral candidacy examination must be taken before registration day of the fifth term of residence as a post-M.S. student or equivalent and will comprise:

- a section where the student will be questioned on the content of courses taken during graduate residence in which he or she will be expected to demonstrate an understanding of the major field of interest;
- a discussion of a brief research report describing accomplishments to date, including reading, study, and plans for future research. The student must present the report to the examining committee at least ten days before the examination.

Thesis and Final Examination. Copies of the completed thesis must be provided to the examining committee two weeks prior to the examination. The date for the final oral examination is decided at the discretion of the major professor and the division chairman to allow, as necessary, for such matters as publication of the examination in the Institute calendar. The oral examination principally covers the work of the thesis; the examining committee will consist of such individuals as may be recommended by the chairman of the division and approved by the Dean of Graduate Studies.

Subject Minor in Civil Engineering
A student majoring in another branch of engineering, or in another division, may, with the approval of the civil engineering faculty, elect civil engineering as a subject minor. At least 54 units of approved courses must be taken, and an oral examination must be passed.

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 neurobiology, computational devices, information theory, emergent or collective systems, parallel computation, modeling, and complex systems, in conjunction with an appropriate depth of knowledge in the particular field of the thesis research.

Admission
Applicants for admission to the option should have an undergraduate major in electrical engineering, biology, physics, mathematics, or computer science and a general background that will permit enrolling in advanced courses in the other relevant disciplines. Admitted students will become affiliated with one of the three participating divisions as appropriate to their background and interests. 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
Upon admission each student will be 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. The committee will be the judge of the completion of the breadth requirement, necessary before the candidacy examination. The adviser will be replaced by a research adviser when the direction of specialization is determined, not later than the beginning of the second year.

Categories of Courses
The four categories for the distribution requirements of the option are:
Computer Science and Collective Computation: CNS/EE 124, EE/Ma 126, EE/Ma 127, CS/EE/Ma 129, EE 162, EE 163, CS/EE 181, CNS/Bi/Ph 185
Neurobiology: Bi 150, Bi 152, Bi 154, Bi 157, Bi 161, Bi 162, Bi 211, Bi 212, Bi 217, Bi 218, CNS/Bi 186, CNS 256
Physical Computational Devices: CNS/CS/EE 182, APh/EE 132, APh 181
Mathematics and Modeling: AMa 105, AMa 153, AMa 204, Ph 101, Ph 127, Ph 222, Ph 229, APh 105, CS/CNS 174

Master's Degree in Computation and Neural 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 option breadth requirements (see below), and receiving from a candidacy oral examination committee a recommendation for awarding of the degree.

Degree of Doctor of Philosophy in Computation and Neural Systems
Candidacy. To be recommended for candidacy for the Ph.D., the applicant must satisfy a breadth requirement. This consists of satisfactorily taking at least two course-quarters from each of the four course categories and, in addition, one quarter of CNS 221, Computational Neurobiology. Candidates with a weak background in a category may find it necessary to take courses in preparation for those listed. The committee may, under special circumstances and with the consent of the option representative, adjust this requirement to fit the background or need of a student. Participation in the weekly seminar/colloquium on computation and neural systems is also an integral part of the educational program. To be recommended to candidacy, a student must pass an oral candidacy examination that covers both the depth and the breadth of the student's training. The depth component will evaluate the student's knowledge in the area of the proposed thesis research. In advance of the examination, the student must provide the committee with a written summary of research carried out to date and an outline of the proposed thesis research. The examination must be completed before the close of the second year of residence. The student must have been accepted for thesis research by a research adviser (contingent on passing the examination) before the candidacy examination will be given. The examination committee will consist of five members, including the research adviser and at least three faculty members associated with the option. If the research adviser is not from the option, the general nature of the proposed thesis research must,

at the time of the candidacy examination, be examined for its appropriateness to the option and must be approved by a majority of the option members on the candidacy committee.

Thesis and final examination. The candidate is required to take a final oral examination covering his or her doctoral thesis. 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 final form, and prior to its approval.

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 and rarely takes more than five years. 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, (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 and of an M.S. thesis approved by a computer science faculty member.

Although it is possible for a well-prepared student to complete the M.S. requirements in one academic year, a period of four to five quarters provides an opportunity for a greater variety of courses than the minimum required, and for a deeper involvement in the M.S. research.

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.

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 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 mathematics.

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. 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 is expected to take the Ph.D. qualifying oral examination.

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:

- complete 18 units of research in his or her field of interest.
- obtain approval of a course of study consisting of at least 189 units of advanced courses in electrical engineering or the related subjects listed under the master's degree, except that units in research (e.g., EE 191, and 291) may not be counted in this total. The course taken to satisfy the next requirement may be included in this total. Courses taken to fulfill the requirements for the Master of Science degree may be included also.
- pass 27 units of mathematics courses, as approved by the student's faculty adviser, with no grade lower than C.
- pass a qualifying oral examination covering broadly the major field and minor program of study. This examination is normally taken near the end of the second year of graduate study.

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.

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). In addition, an oral examination is required, normally taken following completion of the course of study.

Engineering Science

Aims and Scope of Graduate Study in Engineering Science

The engineering science option at Caltech is designed for students interested in subjects that form the core of new "interdisciplinary" sciences. These branches of science provide the basis for the growth of modern technology. Students may choose 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

One of the following courses in mathematics is required: AMa 101 abc, Methods of Applied 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

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:

- 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 AMa 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 candidates' knowledge in their specialized fields of research.

Subject Minor in Engineering Science
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 information from several fields in achieving solutions. Opportunities for interactions among 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, including, for example, energy-environment relationships. 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. 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 3 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):

- air quality
- water quality
- 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 course units). Students who have not had AMa 95 abc or its equivalent are required to include AM 113 abc or AM 114 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:

Air quality: Env 116, Env 170, ChE/Env 157, ChE/Env 158, ChE/Env 159, Ge 152 c.

Water quality: Env 142 ab, Env 143, Env 146, Env 147, Env 242 abc, Bi/Ch 110 abc, Bi/Ch 132 ab, ChE 101, ChE 151 c, ChE/Ch 164, ChE 165, Ch 117, Ch 118 ab, Ge 152 ac, Ge 140 a.

Applied and environmental biology: Env 144, Env 145 ab, Env 147, Env 166, Env 168, Env 206, Env 208, Env 210, Bi/Ch 110 abc, Bi 122, Bi 180, ChE 163.

Fluid mechanics and transport: Env 112 abc, Env 214 abc, ChE 103 abc, ChE 151 ab, Ge 152 ab, CE/ME 101 abc, CE 111, CE 113 ab, CE 210 ab, CE 212, CE 213.

Applied mathematics: AMa 101 abc, AMa 104, AMa 105 ab, AMa 181 abc, AM 113 abc, AM 114 abc, AM 125 abc, EE/ChE 170 ab, Ma 112 abc.

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 chemistry, aquatic chemistry, applied microbiology, marine ecology, environmental fluid mechanics, water resources, environmental health engineering, hydraulic engineering, 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 guidelines described below, and as approved by the faculty of environmental engineering science.
- pass at least 27 units of course work in advanced mathematics in one of the following courses or sequences as recommended by the thesis adviser: AMa 101 abc; AMa 104, 105 ab; AM 125 abc; Ph 129 abc; Ma 112 abc; or a satisfactory substitute.
- pass the oral candidacy examination.

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.

Minor Course Requirement. Each student is expected to take a subject minor of 45 or more units, for which the requirements in each subject area are delineated in the catalog. Normally, the subject minor will be administered by a division other than Engineering and Applied Science, but it can be taken in another program within this division if that program is sufficiently different from EES.

Oceanography may be chosen as a subject minor when the required number of course units is taken in approved courses at the Scripps Institution of Oceanography under the exchange arrangement described on page 145. In this case, a professor from SIO will be invited to be a member of the committee for the final examination.

Under exceptional circumstances, in lieu of a subject minor, the EES faculty may approve an alternative program of 45 or more units comprising two or three closely related courses given by two divisions or options, provided that the program has rationale and coherence. If a full-year course is dropped after the first term, that term's work may not be used as credit toward the alternative requirement. A three-term course may be dropped after two terms, and credit received in special circumstances. If humanities or social science courses are elected as part of an alternative program, at least 18 units must be taken in a specific subject. Reading courses or seminars may not be counted as part of this 45-unit requirement.

Minimum Number of Units. The minimum number of units of graduate work is 162, including the major, minor, and required advanced math courses, but excluding research units. Students may not count AM 113 abc or AM 114 abc as part of the required minimum for satisfying this requirement. Only students with significant prior course work in the environmental field will be able to propose a satisfactory program of the minimum 162 units. 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 ten days before the examination. The report will describe accomplishments to date, including reading, study, 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 executive officer for approval. The proposed program must consist of 45 or more units in Env courses or in closely related courses of other options. 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 is 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. 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 strongly urged to submit Graduate Record Examination (GRE) scores for the aptitude tests and the advanced test in their field of undergraduate specialty. 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 four options are geology, geochemistry, 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 take a placement exam in the week preceding the beginning of instruction for the first term. The exam covers basic mathematics, physics, and chemistry. Afterward, the student meets with his or her adviser prior to registration and selects courses based in part on the results of the placement exam.

Students are encouraged to register for at least 9 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 formulation of propositions for the Ph.D. oral examination or orientation toward Ph.D. research.

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, and 109. More advanced courses may be substituted for Ge 101, 102, or 103, subject to approval by the instructor and the division faculty.

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 student will continue to have a separate academic adviser.

The qualifying examination is the oral defense of two research propositions, each supported by a succinct statement of the problem and of the candidate's specific approach to it. 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 chairman's office.

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 should be responsible for the basic general information covered in the four courses, Ge 101, 102, 103, and 104. Students are required to take three of the courses (Ge 101, 102, 103, and 104) outside of their option. Students may petition to drop one or more of these three courses, with approval of the appropriate option faculty, if they already have substantial academic training in that field. Oral presentation, Ge 109, is required of all degree candidates but does not count for 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, in 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 will 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. A first draft of the thesis must be submitted to the division chairman by April 1. The final oral examination for the doctorate will be scheduled following submission of the thesis 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 staff 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.

The student's progress toward meeting these requirements will be monitored annually by the faculty. Satisfactory progress includes meeting the following schedule:

End of first academic year (third term): submission by the student 1) of tentative titles of propositions for review by the qualifying examination committee; and 2) of courses planned to satisfy the Ph.D. requirement for review by the option.

End of second academic year: 1) passing oral exam; 2) approval by the option of courses planned to satisfy candidacy requirements; 3) submission of a tentative thesis topic and adviser.

End of third academic year: 1) satisfactory completion of course requirements; 2) satisfactory completion of other requirements including selection of thesis topic and adviser, 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. In cases where in the opinion of the faculty in the option the student is clearly not showing adequate progress, they may recommend an evaluation by the full faculty. The faculty may deny 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 45 units within the division in subjects other than their own major subject, candidates for the Ph.D. in geology or geobiology must successfully complete a minimum of 90 units of 100–200-level courses, including the 200-level 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 101, Ge 105, Ge 106, Ge 107, 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 abc is required of all majors. For good work in most modern earth science fields, a proficiency in mathematics equivalent to that represented by AM 113 abc (Engineering Mathematics) is essential. Summer study and research at a marine biology laboratory are required of most candidates in geobiology.

Geochemistry. In addition to general Institute and basic division requirements, the candidate for a Ph.D. degree in geochemistry shall acquire at least a minimum graduate background in each of three categories of course work: 1) geology, geophysics, and planetary sciences; 2) chemistry, physics, astronomy, and mathematics; and 3) geochemistry and cosmochemistry. This option assumes a basic knowledge of chemistry at the level of Ch 21 abc as a prerequisite for admission. These requirements may be met by successful completion (normally B average or higher for courses within the division) 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 except that one term of field geology must be included. 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 100–200-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 AMa 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.

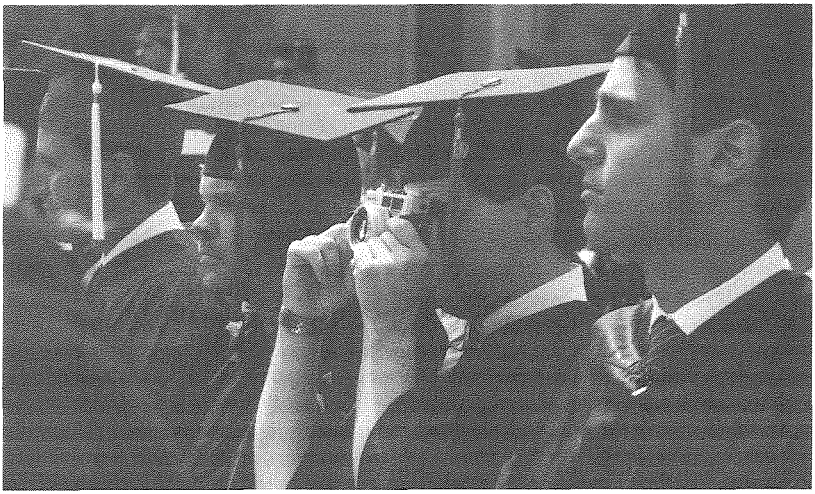
Planetary Science. In addition to general Institute and basic division requirements, the candidate for a Ph.D. degree in planetary science shall acquire at least a minimum graduate background in each of three categories of course work: 1) the earth sciences, 2) physics, mathematics, chemistry, and astronomy, and 3) planetary science (essentially, those courses taught by the planetary science faculty). 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, except that Ge 103 is considered a planetary science course. 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 majoring in 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 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
Students may enter the graduate program in materials science with undergraduate preparation in physics, chemistry, or engineering, as well as materials science. Students interested in terminating their graduate study at the master's level are not normally admitted. The graduate program is designed to give students a deep understanding of issues fundamental to synthesis-structure-property relationships in materials. The program for all graduate students begins with a set of core courses. After meeting the requirements for the M.S. degree, students continuing for the Ph.D. degree are required to 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 two other faculty members will approve his or her course of study. Study for the degree of Master of Science in Materials Science ordinarily will consist of three terms of courses chosen from the following list, and up to 27 units of MS 200, totaling at least 135 units. Completion of these courses within two years with no grade less than a C constitutes the academic requirements for the M.S. degree.

Required Courses

a. APh 110 abc (6 units) or E 150 abc (3 units), seminar

b. 1. MS 120, MS 121, APh/MS 122, Kinetics of Crystal Imperfections, Phase Transformations in Solids, Diffraction Theory and Applications, 27 units
2. APh 105 abc, States of Matter, 27 units
3. APh 114 ab, Solid-State Physics, 18 units
4. Either AM 114 abc, or AM 125 abc, or AMa 101 abc, or Ph 129 abc, Mathematical Methods, 27 units
5. At least 9 units chosen from:
MS 123, Transmission Electron Microscopy Laboratory
MS 131, Crystal Defects Laboratory
6. At least 27 units chosen from:
AM 135 abc, Mathematical Elasticity Theory
APh 114 c, Solid-State Physics
Ph 125 abc, or Ch 125 abc, Quantum Mechanics

Degree of Doctor of Philosophy in Materials Science
Work towards 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. Approximately two years of this time are devoted to research work leading to the doctoral thesis.

Language Requirement. There is no language requirement for the Ph.D. degree.

Minor. No minor is required for the Ph.D. degree. Students are, however, encouraged to take advanced courses appropriate to their particular interests.

Counseling. A faculty member, normally the student's research adviser, is assigned to advise the student on a suitable course program.

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. Successful completion of a course program equivalent to that required for the M.S. degree. Alternatively, if the student has taken equivalent courses elsewhere, he or she must prove competence 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 examination will be based on the student's course work and how it is related to the subject of the presentation.

This examination should be taken in the first term of the second year, and 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 300.

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. The examination 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 acceptable to the materials science faculty. 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 69. 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. 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 5, 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. Students are expected to complete these basic core courses during the first two years, and are encouraged to take additional advanced courses while doing their thesis research.

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 U.S. 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
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, candidacy 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 during the second or third year the student is expected to 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. 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 the 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.

Language Requirement. The student must demonstrate a good knowledge of one of three foreign languages—French, German, or Russian. This requirement is satisfied by passing a written test consisting of translating a passage of a mathematical work chosen by an examiner who is a member of the mathematics faculty. A list of the examiners in each language will be distributed to the students at the beginning of each academic year.

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 insure 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

Master's Degree in Mechanical Engineering
Each student is assigned to a member of the faculty who will serve as the student's initial adviser and who will assist the student in planning a course of study. The program must be approved by the adviser and subsequently by the option representative in mechanical engineering. A total of 138 units is the minimum number required for completion of the master's degree in mechanical engineering. The master's degree is based upon course work based upon the following distribution of courses:

Program Suggested for Mechanical Engineering

- Graduate Mechanical Engineering courses—54 units
  These units should provide a solid base for the student's engineering interest. The courses may be selected from the following list: CE/ME 101 abc, ME 118 abc, ME 120 ab, AM 102 abc, AM 135 abc, AM 151 abc, E/ChE 102 abc, EE/ChE 170 ab.
- Mathematics, Engineering, and Research electives—54 units
  Students who have not taken the equivalent of AMa 95 abc are required to take AM 113 abc or AM 114 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, ME 230; combustion ChE 157, JP 213 abc; engineering design ME 171 ab; multiphase flows ME 202 abc; propulsion JP 121 abc; experimental methods Ae 104 abc. Other courses having a number of 100 or greater may also be taken in Ae, AM, AMa, ME, JP, MS, EE, Env, APh, CS, ChE, CNS. Students who are considering study beyond the master's degree are encouraged to take research units, ME 200, up to a maximum of 27. The research units require a written report and oral presentation.
- Free Electives—27 units
  These units may be selected from any course with a numbering of 100 or greater.
- Engineering Seminar, E 150—3 units

Program for Propulsion
JP 121 abc *must* be included in the graduate mechanical engineering courses.

Degree of Mechanical Engineer
Work toward the degree of Mechanical Engineer requires a minimum of two years following completion of the bachelor's degree or the equivalent. Upon a student's admission to work toward the M.E. degree, a counseling committee of three members of the faculty is appointed. The member of the committee who is most closely related to the student's field of interest serves as the adviser and the chairman. The student should meet with the committee before registration for the purpose of planning his or her work.

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, which succeeds the counseling committee. 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 planned with the counseling committee and finally determined by the supervising committee. The courses must include an advanced course in mathematics or applied mathematics, such as AM 125 abc or AMa 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 AM, AMa, JP, ME, MS, and Ae.

Degree of Doctor of Philosophy in Mechanical Engineering
Work toward the degree of Doctor of Philosophy in mechanical engineering requires a minimum of three years following completion of the bachelor's degree or the equivalent. Approximately two years of this time are devoted to research work leading to a doctoral thesis.

Counseling. A counseling committee of three faculty members is appointed for each student upon admission to work toward a Ph.D. degree in mechanical 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 chairman and interim adviser until this responsibility is assumed by the dissertation supervisor.

In addition, a special joint faculty committee is appointed annually by the faculties in applied mechanics, civil engineering, and mechanical engineering, which meets both collectively and individually with first-year graduate students intending to pursue studies toward the doctoral degree in order to provide further perspective on graduate study and research, as well as to discuss the student's evolving interests.

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 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 referred to above, is confined to elementary but basic topics in the general areas represented by the committee. One purpose of this examination is to identify possible deficiencies in the student's background with a view toward appropriate remedial measures; in addition, the examination contributes to the information used in assessing the student's promise for successful doctoral studies.

To be recommended for candidacy for the Ph.D. degree in mechanical engineering, the student must, in addition to meeting the general Institute requirements:

- complete 12 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 counseling committee and the faculty in mechanical engineering. If the student chooses to take a subject minor, the units thereof may be included in the total of 108, subject to the approval of the faculty in mechanical engineering;
- pass with a grade of at least C an advanced course in mathematics or applied mathematics, such as AM 125 abc, or AMa 101 abc, acceptable to the student's committee and the faculty in mechanical engineering. The requirement in mathematics shall be in addition to the second requirement above, and shall not be counted toward a minor;

- pass an oral examination on the major subject, and, 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 that subject minor.

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 the specialized field of research.

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 group of courses shall differ markedly from the major subject of study or research, and shall consist of at least 54 units of advanced work. The student shall 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 and sound 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.

Students may choose between two major areas of specialization. One, the physics major, encompasses the traditional choices of experimental and theoretical physics. Caltech research opportunities for this major include high-energy physics, nuclear and particle physics, cosmic rays and gamma-ray astronomy, infrared astronomy, submillimeter astronomy, condensed-matter physics, quantum optics, applied physics, gravitational physics, astrophysics, mathematical physics, and theoretical physics.

Students may alternatively elect a major in Physical Computation and Complex Systems (PCCS). The objective of this major is a unified approach to abstraction, modeling, and computation applied to the natural world. This approach is based on a systematic use of physical analogies and methods. The program involves fundamental education in mathematical physics, simple classical and quantum physical systems, fundamental properties of complex systems, physical optimization methods, and the appropriate computational techniques needed for large-scale problem solving on advanced-architecture computers.

A Master of Science degree may be awarded upon completion of what is typically a four-term program of courses. Students are not normally admitted to work toward the M.S. degree in physics unless they are also working for a Ph.D.

Admission
Application blanks for admission to graduate standing and for financial

assistance should be obtained from the Dean of Graduate Studies, California Institute of Technology, Pasadena, CA 91125, and submitted as early as is convenient. While late applications will be considered, applications should whenever possible reach the Graduate Office by January 15. Special inquiries will be welcomed by the chairperson of the Physics Graduate Admissions Committee. Applicants are strongly advised to take the Graduate Record Aptitude Test and Advanced Physics Test. Information may be obtained from the Educational Testing Service, 20 Nassau Street, Princeton, NJ 08540.

Placement Examinations
On the Thursday preceding the beginning of instruction for the student's first term of graduate study, a student admitted to work for an advanced degree in physics is required to take placement examinations to be used as a guide in selecting the proper course of study. These examinations will cover material in mechanics and electromagnetism, quantum mechanics, and mathematical physics, approximately as covered in Ph 106, Ph 125, and Ph 129. 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 exam 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 examinations 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 departmental representative that fulfills the following requirements:

Ph 125 abc .... 27 units
(If this course was taken as part of an undergraduate program or an equivalent course was taken elsewhere, it may be replaced by 27 units of any quantum-mechanics-based course.)

Physics electives .... 81 units
These must be selected from Ph 101, Ph 118, Ph 127, Ph 129, Ph 135, Ph 136, Ph 151, Ph 161, Ph 176, Ph 203, Ph 205, Ph 209, Ph 222, Ph/APh 223, Ph 224, Ph 228, Ph 229, Ph 230, Ph 231, Ph 234, Ph 235, Ph 236, Ph 237, Ph 240, Ph 242.

Other electives .... 27 units
These must be graduate courses from physics or any other option, including humanities.

With the approval of the option representative, a student who has the proper preparation may substitute other graduate courses in science or engineering for some of the physics electives listed above. A master's is not offered in the PCCS major.

Doctor of Philosophy Degree in Physics or PCCS
In addition to the general Institute requirements for a Ph.D., the particular requirements for a doctorate in physics or PCCS include admission to candidacy as described below, passing 27 units of advanced courses in physics

outside the student's research specialty, writing a thesis that describes the results of independent research, and passing a final oral examination based on this thesis and research. Students working toward the Ph.D. degree should complete the requirements for admission to candidacy and the course work as soon as possible.

Admission to Candidacy. Two requirements for admission to candidacy are the passing of an oral candidacy examination (described below) and the passing of two terms of Physics Seminar, Ph 242. In addition, a student must pass two written examinations covering fundamental classical and quantum physics.

The other particular requirements for admission to candidacy differ for the two majors, physics and PCCS. A physics-major student must demonstrate proficiency in any three of the following four areas: the mathematical methods of physics at the level of Ph 129, the applications of quantum physics at the level of Ph 135, the applications of classical physics at the level of Ph 136, and astrophysics. For each of the first three areas, the student may either pass a written candidacy examination similar to the two required exams or pass (with a grade of C or better) all three terms of the corresponding course. Those students choosing astrophysics may substitute for one area, after consultation with the theoretical astrophysics faculty, part of the written astrophysics examination that is given yearly by the astronomy department. No course work other than Physics Seminar is specifically required for the written candidacy exams, but the typical student will profit from taking several of the basic graduate courses, such as Ph 106, Ph 125, Ph 129, Ph 135, Ph 136, and Ph 209.

A PCCS-major student must demonstrate proficiency as described above in two of the four areas: mathematical methods of physics at the level of Ph 129, and applications of classical physics at the level of Ph 136. In addition, the PCCS-major student must pass Ph 151 and Ph 161 with a grade of C or better.

A graduate student who has not been admitted to candidacy by the end of the third year of graduate study at the Institute will not be permitted to register for a subsequent academic year. In addition, it is required that the two mandatory written exams be attempted in a student's first year of graduate study and be passed by the end of the second year. Furthermore, the requirement of demonstrating proficiency in the other subjects must be attempted by the end of the second year and satisfied by the end of the third year. If these deadlines are not met, a student must petition the Physics Graduate Committee before registration for subsequent terms will be allowed. Further guidelines concerning the expected rate of progress in satisfying these requirements are available in the Physics Graduate Office.

The vast majority of students admitted for graduate study in the physics option pass the candidacy requirements. Their purpose is not to "weed out" students, but rather to ensure that, before beginning research, they have both adequate preparation in their research specialty and a broad general knowledge of physics.

Written Candidacy Examinations. Each written candidacy exam is three hours long and covers a particular part of physics that is considered essential, no matter what the candidate's ultimate field of specialization may be. The examinations 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 separate sections while simultaneously learning about research areas through either advanced courses or reading and research courses.

Oral Candidacy Examination. This exam is primarily a test of the candidate's suitability for research in his or her chosen field. Normally a student will have engaged in research (Ph 172 or Ph 173) with the professor who chairs the examination committee. The examination normally covers 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 of the other requirements for admission to candidacy.

Course Requirements. The requirement that students pass two terms of Physics Seminar, Ph 242, before being admitted to candidacy is intended to provide them with a general overview of modern physics research. This course is usually offered in the first two terms of the academic year, and consists of weekly seminars on physics research at Caltech. There is an oral exam based on this material at the end of the term. It is strongly recommended that students take this course in their first year of graduate study at the Institute.

The requirement of 27 units (3 terms of the usual 9-unit course) of advanced physics courses outside a student's specialty may be satisfied by courses drawn from the following list: Ph 101, Ph 118, Ph 127, Ph 151, Ph 161, Ph 176, Ph 203, Ph 205, Ph 222, Ph/APh 223, Ph 224, Ph 228, Ph 229, Ph 230, Ph 231, Ph 234, Ph 235, Ph 236, Ph 237, APh 114, APh 156, APh 190, APh 214, Ay 121–128, Ay 218. The appropriate course or courses for this requirement will normally be clear, but the chairperson of the Physics Graduate Committee will advise students in cases of doubt. The required 27 units may be satisfied with three terms of one course or spread over several courses. Normally, students take many more than the required 27 units of advanced courses, especially courses in their own specialty. The 27-unit requirement for a student in the PCCS major is an application specialization, which must be satisfied by courses covering an area of physics which is a focus of their PCCS research. In cases of doubt, students in the PCCS major must consult with the chairperson as to the appropriate courses to satisfy their application specialization. PCCS students should be aware that many courses in applied mathematics and in computer science, although not required, are highly relevant to their studies.

The student is expected to obtain a grade of C or better in each course. If the student obtains grades below C, the Physics Graduate Committee may review the student's entire record, and if it is unsatisfactory will refuse permission to continue work toward a Ph.D.

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 research as soon as possible and to carry it on in parallel with formal course work; they are advised to take reading and research units (Ph 171–173) prior to being admitted to candidacy. Typically, students will find it desirable to continue graduate study and research for two years after admission to candidacy.

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 or PCCS.

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 conflicts in the scheduling of more than one final oral examination per day.

Subject Minor in Physics or PCCS

Students desiring a subject minor in physics or PCCS should discuss their proposed program with the chairperson of the Physics Graduate Committee. Forty-five units are required for approval of a subject minor in physics or PCCS. A student may only obtain a minor in either physics or PCCS; not in both major areas of specialization. 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. A minor in PCCS requires that one pass all terms of Ph 151 and Ph 161, which can also form part of the total 45-unit requirement. An oral exam may be required, and this should be arranged with the chairperson of 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.

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 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/or matrix algebra; and 3) a course in elementary 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 division's director of graduate studies 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 107.

Course Program
Within the first two years of residence, every student is expected to a) demonstrate adequate competence in the core academic areas of microeconomics, analytical politics, and econometrics; b) pass satisfactorily the preliminary examinations; c) complete six research workshops with a minimum grade of B; and d) present the results of at least one research project to an option-wide colloquium.

- The core curriculum consists of the following eleven one-quarter courses: SS 201 (game theory); SS 202, 203, 204 (analytical politics); SS 205, 206, 207 (microeconomics); SS 222 a, 222 b, 222 c (econometrics); and SS 240 (policy analysis).

  Students are expected to complete these courses by the end of the first year of study. While these courses are not specifically required for a degree, the student must demonstrate competence in each area and must show that omission 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 division director of graduate studies and should be made in consultation with the director and the appropriate faculty. 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.
- At the end of the spring term of the first year, all students must take the preliminary examination. This written exam is given in three parts and covers the areas of analytical politics, microeconomics, and econometrics. To pass the examination, the student must pass all three parts. Students who fail the examination in their first attempt may take it a second time, but that attempt must be made before the beginning of the second year.
- During the second year, each student must complete a minimum of 36 units of work each quarter (with an average grade of B or better), and in that total of 108, a student must successfully complete at least six one-quarter workshops (54 units) and have earned at least a B in each. These research-oriented courses are designed to introduce students to independent research, and all require research papers. The six workshops should be chosen in consultation with the division director of graduate studies and faculty members in the area in which the student wishes to do his or

her thesis research, and with the student's long-term research goals in mind. Students should take at least three workshops in the discipline that they expect to pursue, with a focus on the specific fields in which they will specialize, e.g., applied or theoretical microeconomics or politics, or social scientific history. Students should also bear in mind that a major strength of the program is its multidisciplinary nature, and they are encouraged to sample a variety of fields. In each year there will be workshops in economic theory, applied economics, formal political theory, some substantive area of political science, and econometrics. In addition, although all may not be offered each year, there will be workshops in law, quantitative history, and public policy.

All research papers from the six workshops must be finished and submitted to the social science faculty no later than the end of the spring term of the second year. In addition, the student must present the results on one research project in an option-wide colloquium.

After the completion of the second year, the student's overall performance and research potential will be evaluated by the social science faculty. The student will be admitted to candidacy for the Ph.D. if this evaluation is favorable and if he or she has been accepted for thesis research by an option faculty member.

Degree of Doctor of Philosophy in Social Science

Requirements for the Ph.D. include passing, by the beginning of the second year, a written examination covering the core material in social science, satisfactorily completing six research workshops and presenting a research seminar to the faculty by the end of that year, gaining admission to candidacy, writing a dissertation that reports the findings of independent research, and passing a final oral examination based on the thesis and research. The dissertation is expected to represent publishable, original research with a coherent theme. At the end of each quarter during the third and fourth years, the thesis committee and the option representative will meet to determine whether the student is making sufficient progress in *research* to provide a reasonable expectation of completion within four years. It is expected that students will have completed all requirements for the Ph.D. degree by the end of their fourth year of residency. [1]

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 director of graduate studies.

[1] *A comprehensive description of the option's academic policies can be found in "Information for Students and Advisors in the Social Science Ph.D. Program," available upon request from the Division of the Humanities and Social Sciences.*

Section Five

COURSES

Courses numbered below 100 are taken primarily by undergraduate students. Those numbered from 100 to 199 are taken by both undergraduates and graduates, and those numbered 200 and above are taken primarily by graduate students.

The school year is divided into three terms. The number of units assigned in any term to any subject represents the number of hours spent in class, in laboratory, and estimated to be spent in preparation per week. In the following schedules, figures in parentheses denote hours in class (first figure), hours in laboratory (second figure), and hours of outside preparation (third figure).

At the end of the seventh week of each term, a list of courses to be offered the following term is published by the Registrar's Office. On the day of registration (see Academic Calendar), an updated and revised course schedule is published announcing the courses, class hours, and room assignments for the term.

Abbreviations

Ae	Aeronautics
An	Anthropology
AMa	Applied Mathematics
AM	Applied Mechanics
APh	Applied Physics
Art	Art
Ay	Astronomy
Bi	Biology
BEM	Business Economics and Management
CCO	Campus Computing Organization
ChE	Chemical Engineering
Ch	Chemistry
CE	Civil Engineering
CNS	Computation and Neural Systems
CS	Computer Science
Ec	Economics
EE	Electrical Engineering
E	Engineering
ES	Engineering Science
En	English
Env	Environmental Engineering Science
Ge	Geological and Planetary Sciences
H	History
Hum	Humanities
ISP	Independent Studies Program
JP	Jet Propulsion
L	Languages
Lin	Linguistics
Lit	Literature
MS	Materials Science
Ma	Mathematics
ME	Mechanical Engineering
Mu	Music

PA	Performance and Activities	Ph	Physics
Pl	Philosophy	PS	Political Science
PCCS	Physical Computation and Complex Systems	Psy	Psychology
PE	Physical Education	SS	Social Science

AERONAUTICS

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 101 abc. Fluid Mechanics. *9 units (3-0-6); first, second, third terms.* Begins with study of one-dimensional flows, then moves to consideration of flows with progressively more complex dimensionality. Third term: viscous flows. Topics include thermodynamics of fluid flow, equations of motion; one-dimensional compressible flow, shock waves, nonsteady flow; acoustics, thin airfoil theory; potential flow; kinematics of fluid flow, stress, vorticity; vortex flows; dynamics of real fluids, viscous flow, boundary layer theory. Instructor: Dimotakis.

Ae/AM 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. Instructors: Knauss, Ravichandran.

Ae 103 ab. Vehicle Performance and Dynamics. *9 units (3-0-6); second, third terms. Prerequisites: AMa 95 abc and Ae/ME 130 or equivalent.* Performance and dynamic behavior of aircraft will be discussed. Topics include elementary airfoil and wing theory, speed performance, climb and descent, range, take-off and landing distances, static longitudinal and lateral stability, small amplitude unsteady motions, dynamic stability, responses to controls and disturbances. Instructor: Culick.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6 first term; 1-3-5 second and third terms). Prerequisites: AMa 95 abc or equivalent (may be taken concurrently), Ae/APh 101 abc (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, data acquisition and processing systems. Experiments (second and third terms) in solid and fluid mechanics with emphasis on current research methods, low-speed and high-speed aerodynamics, laser Doppler velocimetry, signal noise. Instructors: Sturtevant, Ravichandran.

Ae 107 abc. Case Studies in Engineering. *9 units (3-0-6); second term. Prerequisite: graduate status or instructor's permission.* Each term, the case history of a major engineering project will be treated in detail. Cases will include aerospace projects and other current engineering programs. Lecturers will, in general, be specialists in their fields from industrial or research organizations. Starting with the economic, political, and technological environment in which the concept originated, the course will proceed to the project initiation, detailed engineering and design, manufacturing operations, and future growth potential. Both project successes and difficulties will be discussed. Grades are based on student projects and attendance (no more than three unexcused absences). Instructor: Hornung.

Ae/AM 108 abc. Finite Element Methods. *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 1990–91.

Ae/ME 130. Introduction to Control of Mechanical Systems. *9 units (3-0-6); first term. Prerequisites: AMa 95 abc and AM 35 abc or equivalent.* Application of feedback analysis and design to mechanical systems, including classical control theory in the frequency and time domains. Stability; performance; methods based in Bode, Nyquist, and root-locus diagrams. Representation in State Space. Analog and discrete systems. Examples taken primarily from mechanical engineering and aeronautics. This course is intended to be the prerequisite of Ae 103 ab and to serve as a first course of controls in robotics. Instructor: Culick.

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: Knauss.

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 of each term.

Ae 201 abc. Advanced Fluid Mechanics. *9 units (3-0-6); first, second, third terms. First term offered jointly with AMa 260 a. Prerequisites: Ae/APh 101 abc or CE/ME 101 abc; AM 125 abc or AMa 101 abc (may be taken concurrently).* Foundations of the mechanics of real fluids. Basic concepts will be emphasized. Subjects covered (not necessarily in the order listed) include physical properties of real gases; the equations of motion of viscous and inviscid fluids; the dynamical significance of vorticity; exact solutions; motion at high Reynolds number; inviscid compressible flow theory; shock waves; similarity for subsonic, transonic, supersonic, and hypersonic flows. Instructor: Staff.

Ae 204 abc. Technical Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh 101 abc, CE/ME 101 abc or equivalents.* 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 design of devices such as mixers, ejectors, diffusers, control valves. Studies of flow-induced oscillations, wind effects on structures, vehicle aerodynamics. Instructor: Coles.

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: Leonard.

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 the campus are intermixed with seminars given by invited lecturers from companies and other research institutions. Graded pass/fail only. Instructor: Ravichandran.

Note: The following courses, with numbers greater than 210, are one-, two-, or three-term courses offered each year 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 212. Shell Theory. *9 units (3-0-6); first term. Prerequisite: instructor's permission.* General mathematical formulation of the theory of thin elastic shells. Membrane and bending stresses in shells. Elastic stability. Surveys of recent advances in the nonlinear theories of stressing and buckling of shells. Not offered 1990–91.

Ae/AM/MS 213 ab. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6); first and second terms. Prerequisites: Ae/AM 102 ab (concurrently) or equivalent and instructor's permission.* Analytical and experimental techniques in the study of fracture in metallic and non-metallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of non-traditional materials. Instructors: Christman, Rosakis.

Ae 221. Theory of Viscoelasticity. *9 units (3-0-6); first term. Prerequisites: Ae 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 1990–91.

Ae/AM 223 ab. Plasticity. *9 units (3-0-6); second, third terms. Prerequisite: Ae/AM 102 abc or instructor's permission.* Theory of dislocations in crystalline media. Characteristics of dislocations and their influence on the mechanical behavior in various crystal structures. Application of dislocation theory to single and polycrystal plasticity. Theory of the inelastic behavior of materials with negligible time effects. Experimental background for metals and fundamental postulates for plastic stress-strain relations. Variational principles for incremental elastic-plastic problems, uniqueness. Upper and lower bound theorems of limit analysis and shakedown. Slip line theory and applications. Additional topics may include soils, creep and rate-sensitive effects in metals, the thermodynamics of plastic deformation, and experimental methods in plasticity. Not offered 1990–91.

Ae 225. Special Topics in Solid Mechanics. *Units to be arranged; first, second, third terms.* 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. Not offered 1990–91.

Ae 232 abc. Numerical Methods in Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh 101 abc, CE/ME 101 abc or equivalent; AM 113 abc or equivalent.* Problem-oriented review of numerical methods for inviscid and viscous incompressible flows. Topics: free and wall-bounded flows; discussion of vortex methods in two and three dimensions; spectral methods. Problems discussed: vortex merging and roll-up, free shear layers, representation of viscous effects, simulation of separated flows, motion of a vortex filament, aircraft wake vortices, interaction of ring vortices, turbulent spot in a laminar boundary layer, applications to homogeneous turbulence and wall-bounded transitional flows. Instructor: Leonard.

Ae 233 ab. Shear Flow Stability. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh 101 abc, AMa 101 abc.* Laminar stability theory as a guide to laminar-turbulent transition. "Inertial" instability illustrated first by the response of two-dimensional compressible free-shear flows to small inviscid disturbances. Distinctive behavior of "subsonic," "sonic," and "supersonic" disturbances. Importance of modern computational techniques in discovering unstable modes. Laminar boundary layer stability and dual role of viscosity; effects of pressure gradient, suction and heat transfer in liquids and gases. Recent work on control of laminar oscillations by utilizing "feedback." Axisymmetric and three-dimensional disturbances. Unresolved problems of response of laminar shear flows to "external" disturbances. Not offered 1990–91.

Ae 234. Hypersonic Aerodynamics. *9 units (3-0-6); first term. Prerequisites: Ae/APh 101 abc, 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 1990–91.

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, transport equations, Chapman-Enskog procedure. Collisionless and transitional flows. Applications. Not offered 1990–91.

Ae 237 ab. Non-Steady Gasdynamics. *9 units (3-0-6); second and third terms.* Gasdynamic discontinuities in liquids, solids, and gases. Waves with phase change and non-adiabatic flows. Shock and detonation wave stability. Continuous non-steady waves. Wave interactions in one- and two-dimensional flow. Boundary layers in non-steady flow. Applications and shock tube techniques. Instructor: Roshko.

Ae 238. Sources of Vorticity. *9 units (3-0-6); second 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, body forces. Unorthodox boundary conditions. Vorticity production due to discretization errors in numerical computations. Not offered 1990–91.

Ae 239. Turbulent Shear Flows. *9 units (3-0-6); third term.* Similarity arguments for classical shear flows; jet, wake, plume, mixing layer, boundary layer. Survey of current research on large coherent structures. Role of such structures in mixing, entrainment, and transport. Not offered 1990–91.

Ae 240. Special Topics in Fluid Mechanics. *Units to be arranged; first term.* Subject matter changes depending upon staff and student interest. Instructor: Hornung.

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. Not offered 1990–91.

ANTHROPOLOGY

An 22. Introduction to the Anthropology of Development. *9 units (3-0-6); first 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: Scudder.

An 101. Selected Topics in Anthropology. *9 units (3-0-6).* Instructors: Staff and visiting lecturers.

An 123. The Anthropology of Rapid Social Change. *9 units (3-0-6); second 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: Scudder.

An 124. The Evolution and Current Status of Small-Scale Human Societies. *9 units (3-0-6); third term. Prerequisite: An 22.* Lectures deal with human and cultural evolution prior to the rise of the pre-industrial city; reading and student projects deal with the implications of the contemporary world for small-scale human societies, and for the Navajo in particular. Instructor: Scudder.

APPLIED MATHEMATICS

AMa 95 abc. Introductory Methods of Applied Mathematics. *12 units (4-0-8); first, second, third terms. Prerequisites: Ma 1 abc, Ma 2 abc, or equivalents.* Introduction to: functions of complex variables; linear ordinary differential equations; special functions; eigenfunction expansions; integral transforms; linear partial differential equations and boundary value problems. Instructors: Keller, Koonin.

AMa 98 abc. Selected Topics. *9 units (3-0-6); first, second, third terms. Prerequisite Ma 2.* Introduction to nonlinear problems. Special methods for solving ordinary differential equations; phase plane, limit cycles, Floquet theory, similarity solutions, methods of characteristics; difference differential equations, generating functions. Applications to nonlinear oscillations, van der Pol equations, stability, resonance; traffic flow, branching processes, random walks, birth and death processes; fluid flow problems, diffusion, solitons. Variational problems. Instructor: Whitham.

AMa 101 abc. Methods of Applied Mathematics I. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 or Ma 109.* Review of basic complex variable analysis; asymptotic expansions; ordinary linear differential equations; Sturm-Liouville theory; eigenfunction expansions; integral transforms; special functions; integral equations; introduction to partial differential equations; elementary theory of nonlinear differential equations. Instructor: Brattkus.

AMa 104. Matrix Theory. *9 units (3-0-6); first term. Prerequisite: AMa 95 or equivalent.* Linear transforms, theory of linear vector spaces, Hilbert spaces. Matrix calculus, vector and matrix norms. Eigenvalue and eigenvector theory, canonical forms, singular value decompositions, inverses and pseudo-inverses, computational linear algebra. Instructor: Siegel.

AMa 105 ab. Introduction to Scientific Computing. *11 units (3-2-6); second, third terms. Prerequisites: AMa 95 and 104 or equivalent.* Numerical linear algebra. Approximation theory. Numerical integration. Numerical solution of ordinary differential equations. Introduction to numerical solution of partial differential equations. Linear programming. Computer assignments will be given. Instructor: Siegel.

AMa/CS 132 abc. Concurrent Scientific Computing. *9 units (3-3-3); first, second, third terms. Prerequisites: basic knowledge of numerical methods and some programming experience.* A course on the application of computers to scientific computing problems. A variety of numerical methods and their implementation on several architectures will be discussed. Homework assignments will include a project on a concurrent computer. Topics: linear algebra computations, fast Fourier transform, multigrid, conjugate gradient, vortex and Monte Carlo methods; vector processors, parallel machines with local and shared memory. Not offered 1990–91.

AMa 151 abc. Perturbation Methods. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 101 or equivalent; may be taken concurrently with instructor's permission.* Uniformly valid approximations in various physical problems.

Generalized boundary layer technique. Coordinate straining techniques; Poincaré's method. Problems with several time scales; averaging techniques; method of Krylov Bogoliubov. Eigenvalue problems. Examples taken from various fields of science. Instructor: Cohen.

AMa 152 abc. Linear and Nonlinear Wave Propagation. *9 units (3-0-6). Prerequisite: AMa 101 or equivalent; may be taken concurrently with instructor's permission.* Mathematical formulation, hyperbolic equations, characteristics, shocks. Combined effect of nonlinearity and diffusion. Wave propagation with relaxation effects. Dispersive waves, group velocity, geometry of waves, nonlinear dispersive waves. Diffraction theory. The emphasis is on solving physical problems, and the mathematical theory is developed through a wide variety of problems in gasdynamics, water waves, plasma physics, electromagnetism. Not offered 1990–91.

AMa 153 abc. Stochastic Processes. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 or Ma 109.* Basic probability and probabilistic approximations; applications to stochastic population theories and stochastic epidemics. Markov chains, random walks and discrete potentials, Brownian motion. Correlations, power spectra, and application to filtering and prediction of stationary processes. Stochastic differential equations, use of Fokker-Planck and Kolmogorov equations. Markov Process methods. Not offered 1990–91.

AMa 156. Numerical Analysis of Ordinary Differential Equations. *11 units (3-2-6); second term. Prerequisites: AMa 95, 104 and 105 or equivalent.* Theory of numerical techniques for linear and nonlinear initial and boundary value and eigenvalue problems. The discussion of the numerical techniques will focus on consistency, accuracy, stability, stiffness, numerical efficiency, etc. Stiff equations and multiple time scales. Computer assignments will be given. Not offered 1990–91.

AMa 161 abc. Applied Functional Analysis. *9 units (3-0-6). Prerequisites: AMa 104, Ma 109, Ma 110, or equivalent.* Introduction to Hilbert and Banach spaces; Sobolev spaces. Linear functionals, dual spaces, linear operators, adjoints. Fredholm theory, spectral theory. Semigroups. Frechet derivatives, Newton's method. Degree theory, singularity theory, bifurcation. Applications to differential equations, integral equations, variational problems, and numerical analysis. Instructor: Luskin.

AMa 181 abc. Mathematical Programming and Game Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 104 or equivalent.* Computer algorithms for linear programming: simplex, Khachian, Karmarkar. Duality; peturbation theory; combinatoric optimization by integer programming: Gomory's method; multi-objective programming; two-person games. Fixed-point theorems of Brouwer, Kakutani, and Schauder. Nash's theorem for *n*-person games. Kuhn-Tucker theory; quadratic and geometric programming; computer algorithms for nonlinear programming. Instructor: Franklin.

AMa 190. Reading and Independent Study. *Units by arrangement.* Graded pass/fail only.

AMa 201 ab. Methods of Applied Mathematics II. *9 units (3-0-6); second, third terms. Prerequisite: AMa 101 or equivalent; may be taken concurrently with instructor's permission.* Integral equations. Volterra and Fredholm theory;

Hilbert-Schmidt theory; variational characterization. Singular integral equations. Cauchy kernels; Hilbert transforms; Hilbert and Riemann problems. Special techniques. Applications to problems in physics. Not offered 1990–91.

AMa 204 abc. Numerical Solution of Partial Differential and Integral Equations. *11 units (3-2-6); first, second, third terms. Prerequisites: AMa 95, 104, and 105, or equivalent.* Finite difference, finite element, and spectral methods for numerical solution of partial differential equations. Discussion of numerical consistency, accuracy, and stability. Explicit and implicit methods of linear and nonlinear time-dependent problems. Multigrid and iterative methods for solution of elliptic partial differential equations. Integral equation formulations; continuation and bifurcation; application to problems in different areas, such as fluid dynamics and geophysics. Computer assignments will be given. Not offered 1990–91.

AMa 205 abc. Numerical Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Familiarity with numerical methods.* The use of numerical techniques in the analysis of problems in fluid mechanics. Emphasis on the application of numerical methods to those topics covered from the analytical point of view in AMa 251. Topics: survey of finite difference, finite element, and spectral methods for the solution of the Navier-Stokes equation; numerical potential theory; simulation of flow past bodies; vortex methods; treatment of boundary layer flows; numerical techniques for the solution of problems in gas dynamics, in particular, treatment of shocks and discontinuities; numerical studies of hydrodynamic instabilities; simulation of flow in porous media. Instructor: Meiron.

AMa 220 abc. Bifurcation Theory and Nonlinear Boundary Value Problems. *9 units (3-0-6). Prerequisite: Some knowledge of differential equations.* Theory and applications of bifurcation and nonlinear boundary value problems in mechanics, fluid dynamics and nonlinear diffusion processes. Lyapounov-Schmidt theory; multiple bifurcations and Newton's polygons; extension of bifurcated branches, secondary bifurcation, perturbed bifurcation and imperfection sensitivity; Hopf bifurcation of periodic solutions; catastrophe theory; nonlinear boundary value and eigenvalue problems; monotonicity methods; stability theory; degree theory; numerical applications and path following. Not offered 1990–91.

AMa 251 abc. Advanced Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh 101 abc or CE/ME 101 abc; AM 125 abc or AMa 101 (may be taken concurrently).* For course description see Aeronautics, Ae 201.

AMa 260 a. Special Topics in Continuum Mechanics, Hydrodynamic Stability, and Turbulence. *9 units (3-0-6); first term. Prerequisites: Ae/APh 101 or CE/ME 101, AMa 101, or equivalent, and instructor's permission.* An introduction to the basic concepts of the theories of the stability of fluid motion and turbulence. Convective instability, quasi-parallel flows, Orr-Sommerfeld equation. Stability of vortices and waves. Homogeneous turbulence; Kolmogorov hypothesis and its extensions. Nonlinear shear waves and shear flow turbulence. Instructor: Saffman.

AMa 261 a. Special Topics in Nonlinear Wave Propagation. *9 units (3-0-6); first term. Prerequisites: AMa 101 and instructor's permission.* Inverse scattering and related techniques for the study of nonlinear waves. Solitons and their interactions. Multiphase nonlinear waves. Recent developments in these areas. Not offered 1990–91.

AMa 290. Applied Mathematics Colloquium. *Units by arrangement.*

AMa 300. Research in Applied Mathematics. *Units by arrangement.*

Other courses particularly suited to a program in applied mathematics include Ma 191, Ma 142, Ma 144, Ma 147, AM 135, AM 136, AM 151, AM 175, AM 176, APh 156, Ph 125, Ph 209, and Ph 236.

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, vibrating systems, Lagrange's equations and Hamilton's principle. Instructor: Hall.

AM 96 abc. Applied Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc.* Basic principles and applications of classical mechanics. Analytical description of motion, including relative motion. Particle mechanics, including energy and momentum principles. Generalized coordinates, principle of virtual work, stability, Lagrange's equations and Hamilton's principle. Rigid body dynamics. Response of mechanical systems to periodic and transient excitations. Applications to such problems as planetary motion, effects of the earth's rotation, rocket motion, impact, gyroscopic motions, vibration isolation, vibration instrumentation, etc. Not offered 1990–91.

AM 97 abc. Analytical Mechanics of Deformable Bodies. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 1 abc and Ma 2 abc.* Introduction to the theory of stress and strain in solid bodies. Applications to beams, columns, plates and shells, torsion, inelastic behavior, numerical and experimental stress analysis, wave propagation, energy methods of analysis. Not offered 1990–91.

Ae/AM 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6).* For course description, see Aeronautics.

Ae/AM 108 abc. Finite Element Methods. *9 units (3-0-6).* For course description, see Aeronautics.

AM 113 abc. Introductory Engineering Mathematics. *12 units (4-0-8); first, second, third terms. Prerequisite: elementary calculus.* Alternative to AM 114 abc, including review of concepts and techniques from calculus and ordinary differential equations. Introduction to complex variables and applications.

Illustrative examples of boundary-value problems for the Laplace equation, the heat equation, and the wave equation. Instructors: Staff.

AM 114 abc. Engineering Mathematics. *12 units (4-0-8); first, second, third terms. For graduate students who have not had the equivalent of AMa 95 abc. Prerequisite: Ma 1 abc, Ma 2 abc, or equivalent.* Includes: basic theory of complex variables and applications, such as conformal mapping, linear differential equations, and special functions; Fourier series and Fourier integrals; solution of boundary-value problems for partial differential equations by separation of variables and by integral transforms. Instructor: Beck.

AM 125 abc. Engineering Mathematical Principles. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 abc, AM 113 abc, or AM 114 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: Wiggins.

AM 135 abc. Mathematical Elasticity Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: instructor's permission.* Cartesian tensors. Kinematics and kinetics of continuous media, constitutive relations for elastic solids. Fundamental problems and related theorems of linearized elastostatics and elastodynamics. Integration theory and applications to specific problems of engineering interest. Instructor: Knowles.

AM 136 abc. Advanced Mathematical Elasticity Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: AM 135 abc or equivalent.* Topics drawn from the more advanced linear theory and nonlinear theory. Specific content varies according to interests of students and instructor. Not offered 1990–91.

AM 141 abc. Wave Propagation in Solids. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 abc, AM 113 abc, or AM 114 abc, or instructor's permission.* Theory of wave propagation in solids with applications; introduction to linear elastodynamics; waves in the infinite elastic medium; reflection and refraction of time harmonic waves at an interface; time harmonic waves in elastic waveguides (rods, plates, layers); wave dispersion. Transient waves in an elastic half space and a waveguide; transient wave scattering and diffraction; boundary value problems; introduction to theory of waves in viscoelastic and plastic media. Not offered 1990–91.

AM 151 abc. Dynamics and Vibrations. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 abc, AM 113 abc, or AM 114 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: Caughey.

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 1990–91.

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, Poincare 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 1990–91.

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 ab. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aeronautics.

Ae/AM 223 ab. Plasticity. *9 units (3-0-6).* For course description, see Aeronautics.

AM 250 abc. Research in Applied Mechanics. *Hours and units by arrangement.* Research in the field of applied mechanics. By arrangement with members of the staff, properly qualified graduate students are directed in research.

APPLIED PHYSICS

APh 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2); first, second terms; six units credit for the freshman laboratory requirement.* 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 diode, 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: Atwater.

APh/ME 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. Instructor: Johnson.

APh 23. Demonstration Lectures in Optics. *6 units (2-0-4); second 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, optical detection and heterodyning. System examples to be selected from optical communications and radar, adaptive optical systems. Instructor: Vahala.

APh 24. Introductory Modern Optics Laboratory. *6 units; third term. Prerequisite: APh 23.* Laboratory experiments to acquaint students with the contemporary aspects of modern optical research and technology. Experiments encompass many of the topics and concepts covered in APh 23. Instructor: Vahala.

APh 50 abc. Quantum Physics of Matter. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 abc, Ma 2 abc, or equivalents.* Quantum mechanics and applications to problems of the three states of matter: solids, gases, and liquids. Topics: bound and free particles, the electromagnetic field, diatomic molecules, quantum systems in thermal equilibrium, and perturbation theory. Additional topics selected from plasma physics and electron transport in solids. Applications such as lasers and semiconductor electronics will be treated along with other topics in physics, depending on the instructor and interests of the students. Instructor: Staff.

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. Instructor: Bellan.

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 the 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 the applied physics faculty.

APh 100. Advanced Work in Applied Physics. 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 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 of first and higher orders; critical phenomena; band theory of solids, liquids, ideal classical and degenerate gases; fluctuations; noise. Instructor: Corngold.

APh 107. Advanced Dynamics. *9 units (3-0-6); third term. Prerequisite: Ph 106 a, b, or equivalent.* Lectures on advanced topics in classical mechanics, such as conservative vs. dissipative systems, integrable systems, the KAM Theorem, "stochasticity and chaos." Examples will be drawn from statistical mechanics and other fields of physics. Instructor: Corngold.

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 50 or Ph 98 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: McGill.

APh/MS 122. Diffraction Theory and Applications. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Principles of electron and x-ray diffraction, and applications in characterizing materials. Topics include: Scattering and absorption of electrons and x-rays by atoms, anomalous scattering. The transmission electron microscope (TEM) and the x-ray diffractometer. Kinematical theory of diffraction: mathematical and graphical treatments; effects of strain, size, disorder, and temperature; bright field and dark field TEM imaging of crystal defects. Dynamical theory of diffraction: Darwin's theory; Bethe's theory; defect contrast in TEM. Special topics in TEM. Instructor: Fultz.

APh/EE 130. Introduction to Optoelectronics. *9 units (3-0-6); first term. Prerequisites: APh 23, 24 or instructor's permission.* Introduction to phenomena, devices, and applications in optoelectronics. Gaussian beam propagation; basic laser theory and discussion of selected lasers; modulation, optical detectors, and noise; system design considerations, with examples from optical communication, radar, and other applications. Instructor: Bridges.

APh/EE 131. Optoelectronic Devices. *9 units (3-0-6); second term. Prerequisite: APh/EE 130 or instructor's permission.* Propagation of light in crystals; electro-optic effects and their use in the modulation of light; an introduction to nonlinear optics; harmonic generation. Semi-conductor lasers. Design examples of practical interest. Offered in alternate years; not offered 1990–91.

APh/EE 132. Fourier Optics. *9 units (3-0-6); third term. Prerequisite: AMa 95 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. Topics: scalar diffraction theory; the lens as a Fourier transforming element; coherent and incoherent imaging; optical information processing systems; holography. Not offered 1990–91.

APh/CNS/EE 133. Optical Computing. *9 units (3-0-6); first 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 section, 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. Instructors: Atwater, Nicolet.

APh/MS 141 abc. Ion Beam Analysis Laboratory. *5 units (0-4-1); first, second, third terms; no more than two terms for credit. Prerequisite or concurrently: APh 140.* Laboratory instruction in the use of backscattering spectrometry for the characterization of materials. Operation of solid-state detector and electronics chain. System calibration. Recording of spectra. Quantitative evaluation of spectra. Channeling in single crystalline films and bulk crystals. Instructors: Atwater, Nicolet.

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: 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, including orbits of charged particles in electric, magnetic, and gravitational fields; continuum magnetohydrodynamics and elementary stability theory; transport processes such as conductivity and diffusion, Vlasov equation, waves, and oscillations in plasmas. Examples from plasmas used in controlled thermonuclear fusion research (e.g., tokamaks, mirrors, pinches). Instructor: Gould.

EE/APh 180. Solid-State Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

APh 181 ab. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6); first, second terms.* Introduction to the concepts of semiconductor devices, based on underlying physical properties of semiconductors. Electronic and chemical equilibrium in the bulk semi-conductor and near interfaces, e.g., pn junctions, surfaces. Kinetics of carrier generation-recombination and transport to first order. Traditional and novel methods of device fabrication. Applications will be made to a wide variety of devices and attention given to feasible schemes for device construction. Instructor: Nicolet.

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. Offered in alternate years. Instructor: Yariv.

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 1990–91.

Ph/APh 223 abc. 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 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

Art 101. Selected Topics in Art History. *9 units (3-0-6). Advanced credit to be determined on a course-by-course basis by the instructor.* Instructors: Staff.

Art 103. Ancient Art. *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 300 A.D. 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 foundations of the Western artistic tradition. Instructor: Thalmann.

Art 106. Medieval Art. *9 units (3-0-6).* A study of Western European artistic developments from the disintegration of the Roman world, circa 476 A.D., to the age of the great cathedrals through the 14th century. The period is art-historically divided into four general categories: early Christian, Carolingian, Romanesque, and Gothic. The diverse historical forces at work during this long period produced a correspondingly varied art. 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).* 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.

Art 109. Northern European Art: 1400–1650. *9 units (3-0-6).* A comprehensive survey of artistic developments in Northern Europe 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, Brueghel, Holbein, Rubens, Van Dyck, Hals, and Rembrandt. Instructor: Howard.

Art 110. Baroque Art. *9 units (3-0-6).* 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, Velasquez, 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.

Art 112. British Art of the Georgian Period.* *9 units (3-0-6).* Introduction to visual arts and vocabularies of analysis for the study of painting through an in-depth study of British art of the Georgian period in the Huntington Art Gallery collection. Instructor: Wark.

Art 115. Art of the Nineteenth Century. *9 units (3-0-6).* A survey of nineteenth-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.

Art 118. Art of the Twentieth Century. *9 units (3-0-6).* A survey of European and American painting, sculpture, and architecture of the twentieth century. The lectures will focus on issues such as the ways in which artists tried, succeeded, or failed to fit together personal and public meaning in their art, the problems facing architects in an industrial society, the claims and strategies of the avant-garde, why art became abstract, and what is meant by the claim during this period that "art is dead." Discussion will center on the relationship between art and politics, technology, and individual artistic expression. Instructor: Bennett.

ASTRONOMY

Ay 1. Introduction to Astronomy. *9 units (3-1-5); second term.* Primarily for freshmen; surveys astronomy and astrophysics, emphasis on application of physics in astronomy. Graded pass/fail. Instructor: M. Cohen.

Ay 20. Basic Astronomy and the Galaxy. *11 units (3-2-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc.* Astronomical terminology. Stellar masses, distances, and motions. Star clusters and their galactic distributions. Stellar spectra, magnitudes, and colors. Structure and dynamics of the galaxy. Laboratory exercises including double star orbits and the use of an astrograph. Instructor: Mould.

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); third term. Prerequisite: Ay 20.* The extragalactic distance scale. Clusters of galaxies. Introduction to cosmology. Balance of matter and radiation in the universe. Instructor: Readhead.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

Ay 22. Solar System. *9 units (3-0-6); second term.* Physics of the sun. Surface phenomena of the sun, formation of spectral lines. Solar activity, sunspots, and flares. The solar corona and solar wind. Physics of the planetary system. Planetary magnetospheres and atmospheres, surface phenomena. Comets. Instructor: Zirin.

Ay 30. Current Trends in Astronomy. *3 units (2-0-1); second term.* Weekly seminar designed for sophomore astronomy majors only, held in faculty homes in the evening, to introduce students to the faculty and their research. Graded pass/fail. Instructor: Zirin.

Ay 42. Research in Astronomy and Astrophysics. *Units in accordance with work accomplished.* Properly qualified undergraduates may, in their senior year, undertake independent or guided research with the goal of preparing a senior thesis. Graded pass/fail.

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 101. Physics of Stars. *11 units (3-2-6); second 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. Instructor: Oke.

Ay 102. Physics of the Interstellar Medium. *9 units (3-0-6); third term. Prerequisite: Ay 20.* An introduction to fluid mechanics, sound waves, and shock waves. Introduction to magnetohydrodynamics, Alfven 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. Instructor: Scoville.

Ay 110. Senior Seminar in Astrophysics. *6 units (2-0-4); first term.* Designed for Ay seniors. Seminar on astrophysical topics of current interest. Lectures given by the students. Emphasis on topics requiring a synthesis of previous formal course work. Instructor: J. Cohen.

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisites: Ay 101 (undergraduates); Ph 98 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: Libbrecht, Phinney.

Ay 122. Astronomical Measurements and Instrumentation. *9 units (3-0-6); first 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: Kulkarni, Oke.

Ay 123. Stellar Structure and Early Evolution. *9 units (3-0-6); third term. Prerequisites: Ay 101 (undergraduates); Ph 98 or equivalent.* Stellar structure and evolution. Polytropes, radiative transport, convection, nuclear energy generation, main sequence. Hayashi track, advanced stages of evolution, pulsations, rotation. Stellar atmospheres. Instructor: J. Cohen.

Ay 124. Structure and Dynamics of Galaxies. *9 units (3-0-6); second 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: Djorgovski.

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ay 21 (undergraduates) and 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: Blandford.

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: Kulkarni, 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: Sargent.

Ay 128. Solar Physics. *9 units (3-0-6); second term. Prerequisites: Ay 22 (undergraduates) and Ph 106 (or equivalent).* The detailed structure and dynamics of the sun, including the solar interior, the neutrino problem, the photosphere, chromosphere, corona and solar wind, convection and the solar dynamo, sunspots and faculae, helioseismology, solar flares, and solar-terrestrial relations. Instructor: Libbrecht.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6).* For course description, see Geology.

Ay 141 abc. Research Conference in Astronomy. *2 units (1-0-1); first, second, third terms.* These conferences consist of reports on investigations in progress at the Caltech Submillimeter, Las Campanas, Palomar, and Big Bear observatories and the Owens Valley Radio Observatory, and on other research that is of current interest. Graded pass/fail.

Ay 142. Research in Astronomy and Astrophysics. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of research outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy. Graded pass/fail.

Ay 143. Reading and Independent Study. *Units in accordance with work accomplished.* The student should consult a member of the department and have a definite program of reading and independent study outlined. Approval by the student's adviser must be obtained before registering. 36 units of Ay 142 or Ay 143 required for candidacy. Graded pass/fail.

Ay/EE 144. Synthetic Imaging by Interferometers: Radio, Infrared, and Optical. *9 units (3-0-6); third term.* The theory of coherence, interferometry, and aperture synthesis observations at radio, infrared, and optical wavelengths. Emphasis is given to the problems of image synthesis, applications in astronomy, geodesy, spacecraft tracking and ranging, and to advances in technology which have pushed the frequency of operation to millimeter wavelengths and to the infrared and optical regions of the spectrum. Instructor: Kulkarni.

Ay 211. Extragalactic Astronomy. *9 units (3-0-6).* Course for graduate students in astronomy, including discussion of recent research in extragalactic astronomy and cosmology. Given in alternate years. Not offered 1990–91.

Ay 212. Topics in Astronomy. *9 units (3-0-6); third term.* A course for graduate students in astronomy. Topic for 1990–91 will be the large-scale structure of the universe. Instructors: Djorgovski, Mould. (Note: Ph 224 c counts as equivalent to Ay 212 for Ay graduate students.)

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Seminar for advanced students on recent developments in astrophysics. The current theoretical literature will be discussed by the students. Given in alternate years. Not offered 1990–91.

Ay 218. High-Energy Astrophysics. *9 units (3-0-6); first term. Prerequisites: Ay 125, Ph 106, and Ph 125 or equivalent.* Topics covered vary from year to year. Given in alternate years. Not offered 1990–91.

Ay 234. Seminar in Radio Astronomy. *6 units (2-0-4); third term. Prerequisite: Ay 125.* Recent developments in radio astronomy for the advanced student. Current publications and research in progress will be discussed by students and staff. Given in alternate years. Topic for 1990–91 will be unified theories of active galaxies and quasars. Instructors: M. Cohen, Readhead.

Ay 235. Research Seminar. *1 unit (1-0-0); first term.* Will present seminars on current research interests of the astronomy faculty to graduate students during the fall term. Particular emphasis will be given to research projects of short duration (~3-6 months) which might prove suitable for graduate students to undertake during their first two years. Instructor: Djorgovski.

BIOLOGY

Bi 5. Introduction to Modern Biology. *6 units (3-0-3); third term.* A course designed as a survey of modern biology including such areas as developmental biology and cell physiology, which will be examined from biochemical, genetic, and evolutionary viewpoints. Although designed for nonmajors, may be taken by potential biologists, but not for credit toward biology option requirements. Graded pass/fail. Instructors: Anderson, Revel.

Bi 7. Introduction to Molecular Biology; Structure and Properties of Biological Molecules. *9 units (3-0-6); first term.* This course will prepare the student for Bi 8 and Bi 9. The features of biological molecules which are specially important to their role in the cellular economy will be emphasized. Among the topics covered will be the chemistry and properties of proteins, DNA, RNA, and carbohydrates, including their synthesis and metabolism. While not required, the course is strongly recommended for students who intend to major in biology. Graded pass/fail. Instructors: Zinn, Revel.

Bi 8. Introduction to Molecular Biology; Organization and Expression of Genetic Information. *12 units (3-3-6); 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 organization and expression of genetic information, including what is commonly called molecular biology, and introduction to topics in developmental biology and immunology. Graded pass/fail. Instructors: Simon, Wold.

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 (0-4-2); third term. Prerequisite: Bi 8; designed to be taken concurrently with Bi 9.* Introduction to basic methods in cell biological research, including subcellular fractionation, practical enzymology and immunochemistry, use of radioisotopes, gel electrophoresis of proteins and nucleic acids, and light and electron microscopy. Instructor: Wold.

Bi 11. Organismic Biology. *9 units (3-3-3); first term. Prerequisite: Bi 9.* Survey of the principal kinds of organisms and problems they solved in adapting to various environments. Instructor: Brokaw.

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; first, second, third terms.* Study and discussion of special problems in biology, usually involving regular tutorial sessions with instructors. To be arranged through the undergraduate adviser before registration. Graded pass/fail. Instructors: Strauss and staff.

Bi 90 abc. Undergraduate Thesis. *12 or more units per term; first, second, third terms. Prerequisites: 18 units of Bi 22 or equivalent research experience in the research area proposed for the thesis, and instructor's permission.* Intended to extend opportunities for research provided by Bi 22 into a coherent individual research project, carried out under the supervision of a member of the biology faculty. Normally involves three or more consecutive terms of work in the junior and senior years. The student will formulate a research problem based in part on work already carried out, evaluate previously published work in the field, and present new results, in a thesis format. First two terms graded pass/fail; final term graded by letter on the basis of the completed thesis. Instructors: Revel and staff.

Bi/Ch 110 abc. Biochemistry. *12 units (4-0-8); first, second, and third terms. Prerequisite: Ch 41 or instructor's permission. Instructors recommend Bi 8 as background for Bi/Ch 110 b and c.* Lectures and discussions on the molecular basis of biological structure and function. Emphasizes macromolecular structure and the metabolic processes involved in energy storage and utilization; storage, transmission, and expression of genetic information in prokaryotes and eukaryotes. Other topics in biochemistry of higher organisms: molecular regulatory mechanisms and the biochemistry of cell membranes. Instructors: Campbell, Kennedy, Parker, Richards.

Bi 114. Immunology. *12 units (4-0-8); second term. Prerequisites: Bi 8, Bi 9, Bi 122 or equivalent; Bi/Ch 110 a recommended.* The cellular and molecular mechanisms involved in immune phenomena. Immunoglobulin chemistry, developmentally programmed gene rearrangements, molecules mediating cell-cell recognition, functions of lymphokines, and selection mechanisms shaping the immune repertoire. Instructor: 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 1990–91. Instructor: Strauss.

Bi 122. Genetics. *9 units (3-0-6); second term. Prerequisite: Bi 8 or Bi 9, or instructor's permission.* Lecture and discussion course covering basic principles of genetics. Instructor: Meyerowitz and staff.

Bi 123. Genetics Laboratory. *6 units (0-4-2); second term. Prerequisite: Bi 122 (may be taken concurrently).* Laboratory exercises illustrating genetic principles and techniques, designed to accompany Bi 122. Instructor: Lipshitz.

Bi 125. Principles and Methods of Gene Transfer and Gene Manipulation in Eukaryotic Cells. *9 units (3-0-6); 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. Given in alternate years; not offered 1990–91. Instructor: Attardi.

Bi 127. Regulation of the Cell Cycle. *6 units (2-0-4); second 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. Given in alternate years; not offered 1990–91. Instructor: Wold.

Bi/Ch 132 ab. Biophysics of Macromolecules. *9 units (3-0-6); second, third terms. Recommended: Bi/Ch 110 (or taken concurrently).* 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. Instructors: Chan, Rees, Richards.

Bi 135. Principles of Three-Dimensional Protein Structure. *6 units (3-1-2); first term.* The forces determining the folding of proteins into their unique tertiary structures. Protein structures will be classified by common organization of secondary structural elements, and structural motifs and their influence on function will be explored. Topics will include enzyme and antibody structure and function, virus structures, and methods of secondary and tertiary structure prediction (and their accuracy). Students will pick a protein structure to study in detail using molecular graphics on a color graphics display. Instructor: Bjorkman.

Bi 137. Multicellular Assemblies. *9 units (3-0-6); third term. Prerequisite: Bi 9 or consent of instructor.* Aspects of the cellular interactions involved in formation and maintenance of the hierarchy of tissues and organs in multicellular organisms. Topics include cell membranes, cell movements and aggregation, cellular adhesion, intercellular communication, the organization of epithelial and connective tissues, and the histophysiology of a few typical organs. Given in alternate years; offered 1990–91. Instructor: Revel.

Bi 145. Animal Physiology. *9 units (3-0-6); third term. Recommended prerequisites: Bi 9, Bi 11.* Discussion of selected topics in animal physiology. Mammalian systems will be emphasized, but information from other groups will be drawn upon where relevant. Particular focus on mechanisms of muscle contraction and its regulation, on the supply of oxygen to muscle and other tissues, and on the regulation of water and solute contents of cells, tissues, and the body. Given in alternate years; not offered in 1990–91. Instructor: Brokaw.

Bi 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 experience with the experimental preparations discussed in the course. Instructors: Laurent, Van Essen.

Bi 152. Behavioral Biology. *6 units (2-0-4); second term.* Introduction to ethology and behavioral genetics. Topics: causation, development, evolution, and genetic analysis of animal behavior, with examples from both invertebrates and vertebrates. Instructors: Benzer and Konishi.

Bi 154. Topics in Experimental Psychology. *6 units (2-0-4); second term.* Introductory lectures in advanced (visual and auditory) perception. Although memory and higher brain functions in humans will be discussed, the emphasis will be on early vision, particularly on stereoscopic depth and motion perception, preattentive texture discrimination, and focal attention. Lectures will include displays, movies, and illustrations of major perceptual phenomena. Instructor: Julesz.

Bi 156. Neurochemistry. *9 units (3-0-6); third term. Prerequisite: Bi 150 or instructor's permission.* A lecture and discussion course covering the biochemistry and molecular biology of processes fundamental to nervous system function. These include neurotransmitter/neuropeptide synthesis and release, neurite outgrowth, receptor and ion channel function, and myelination. Other topics include neurotrophic factors and putative cell surface recognition molecules. The relationship of these subjects to mental illness and learning will be considered. Given in alternate years; not offered 1990–91. Instructors: Anderson and Patterson.

Bi 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. Given in alternate years; offered 1990–91. Instructor: Allman.

Bi 158. Primatology. *9 units (3-1-5); third term.* Evolutionary and behavioral biology of primates. Topics include fossil primates, comparative anatomy, physiology and ethology of primates, and tool invention and symbolic communication in primates. Given in alternate years; not offered 1990–91. Instructor: Allman.

Bi 161. Cellular Neurobiology Laboratory. *6 units (0-4-2); second term. Prerequisite: Bi 150 or instructor's permission.* Principles of cellular neurobiology and membrane biophysics illustrated using favorable preparations, such as frog nerve-muscle synapse and cultured nerve and muscle tissue. Students conduct all aspects of experiments, including dissection, fabrication of microelectrodes, intracellular stimulation and recording, and patch recording of single membrane channels. Graded pass/fail. Given in alternate years; offered 1990–91. Instructor: Lester.

Bi 162. Central Nervous System Laboratory. *10 units (0-8-2); second 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. Given in alternate years; not offered 1990–91. Instructor: Bower.

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 180. Methods in Molecular Genetics. *12 units (2-8-2); first term. Prerequisites: Bi 122 and instructor's permission.* An introduction to current research tools of molecular genetics. Students perform a series of structured experiments to familiarize themselves with basic genetic approaches, including mutant selection, genetic mapping, gene cloning, and gene product analysis. Students then confront an unresolved research problem in biology to be addressed by both designing and executing their own experiments. Graded pass/fail. Instructor: Emr.

CNS/Bi/Ph 185. Collective Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/Bi 186. Vision: From Computational Theory to Neuronal Mechanisms. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

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 1990–91. 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: Lipshitz, Meyerowitz, Sternberg.

Bi/Ch 202 abc. Biochemistry Seminar. *1 unit; all terms.* A seminar on selected topics and on recent advances in the field. Instructors: Staff.

Bi 204. Genetics Seminar. *2 units; all terms.* Reports and discussion on special topics. Instructors: Meyerowitz, Simon.

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 biochemistry of processes mediated by the neuronal cell membrane. Particular emphasis on current aspects of synaptic transmission. Given in alternate years; not offered 1990–91. Instructor: Lester.

Bi 212. Topics in Ethology and Behavioral Genetics. *6 units (2-0-4); second term.* Reading and discussions of original papers related to animal behavior and its analysis by ethological and genetic methods. Given in alternate years; not offered 1990–91. Instructors: Benzer and Konishi.

Bi 214. Control of Development and Function in Hematopoietic Cells. *6 units (2-0-4); first term. Prerequisites: Bi 114 or graduate standing.* An advanced seminar based on reading from the current literature. Mechanisms of cell fate determination and lineage commitment, cell activation, and physiological function will be discussed, with an emphasis on lymphocytes. Given in alternate years; not offered 1990–91. Instructor: Rothenberg.

Bi 217. Central Mechanisms in Perception. *6 units (2-0-4); first term.* Reading and discussions of behavioral and electrophysiological studies of the systems for the processing of sensory information in the brain. Given in alternate years; offered 1990–91. Instructor: Allman.

Bi 218. The Physiological Basis of Behavior. *6 units (2-0-4); third term.* Reading and discussions of original papers dealing with the problem of how nerve cells act to generate behavior. Several simple reflex, rhythmic, and learning behaviors are considered. Individual cellular elements and synaptic interactions responsible for generating each behavior are examined in detail. Other topics include modulation of motor output by sensory input and experience. Given in alternate years; not offered 1990–91. Instructor: Tanouye.

Bi 219. Developmental Neurobiology. *9 units (2-0-7); third 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 generation of specific synaptic connections and molecular basis underlying it. Given in alternate years; offered 1990–91. Instructor: Patterson.

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; offered 1990–91. Instructor: E. Davidson.

Bi 222. Biochemistry of the Nervous System. *6 units (2-0-4); second term. Prerequisites: graduate standing or permission of instructor.* Reading and discussion illustrating recent applications of biochemical and molecular biological techniques to the study of signaling in the nervous system. Topics will include structural and functional studies of synapses and synaptic proteins; neuromodulation by second messenger pathways; regulation of gene expression in mature neurons; and possible molecular mechanisms underlying the formation and storage of memories. The course will emphasize reading and evaluation of recent research papers. Given in alternate years; offered 1990–91. Instructor: Kennedy.

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 transformation 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, membrane physiology and assembly. Given in alternate years; offered 1990–91. Instructor: Attardi.

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. Instructor: Dreyer.

Bi 250 abc. Issues and Principles in Modern Biology. *4 units (2-0-2); all terms.* Graduate seminar emphasizing the fields of research represented in the biology division. Topics will vary, reflecting the interests of the faculty. Reading and discussion will be required. Instructors: Anderson, Lazarides, Simon, and staff.

Bi 270. Special Topics in Biology. *Units to be arranged; first, second, third terms.* Students may register with permission of the responsible faculty member.

Bi 299. Graduate Research. *Units to be arranged; first, second, and 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: Staff.

BEM 102. Topics in Management Science. *9 units (3-0-6). Prerequisite: Ec 11.* 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. Not offered 1990–91. Instructors: Staff.

BEM 103. Introduction to Finance. *9 units (3-0-6); second 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: Hughson.

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 110. Topics in Business Economics. *9 units (3-0-6). Prerequisites: consent of instructor.* Selected topics in business economics. Instructor: Staff.

CAMPUS COMPUTING ORGANIZATION

CCO 1 abc: Computing Fundamentals. *6 units (2-0-4); first, second, third terms.* An introductory course covering the basics of computers and their use, designed for students who have no computing experience. Lectures cover basic principles of computer hardware, operating systems, and representation and storage of information in the computer. Each term will teach the use of a single language using well-documented examples; students will be expected to write several programs. CCO 1 a will cover C; CCO 1 b will cover PASCAL; and CCO 1 c will cover FORTRAN. Only one term can be taken for credit. With permission of the instructor, students may audit additional terms to broaden language experience. Instructors: C. Ray, staff.

CHEMICAL ENGINEERING

ChE 10. Introduction to Chemical Engineering Systems. *9 units (3-3-3); third term.* An introduction to the breadth of chemical engineering through several short-term projects supervised by individual chemical engineering faculty. Areas covered include biochemical engineering, fluid mechanics, polymer physics, and dynamics and control. Instructors: Bailey, Brady, Kornfield, Seinfeld.

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; equations of state; thermochemical calculations. Thermodynamic cycles; multicomponent systems, excess properties, fugacities, activity coefficients, and models of nonideal solutions. Chemical reaction equilibria; phase equilibria and applications; thermodynamics of ionic solutions and electrode processes. Instructor: Gavalas.

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. Instructor: Staff.

ChE 101. Chemical Reaction Engineering. *9 units (3-0-6); second term. Prerequisites: Ch 21 a, ChE 103 a.* Chemical kinetics. Ideal chemical reactors. Energy balances in chemical reactors. Residence time distributions. Noncatalytic fluid-solid reactions. Fluid-fluid heterogeneous reactions. Heterogeneous reactors. Instructor: Flagan.

E/ChE 102 abc. Systems Analysis and Control. *9 units (3-0-6).* For course description, see Engineering.

ChE 103 abc. Transport Phenomena. *9 units (3-0-6); first, second, third terms. Prerequisites: AMa 95 or AM 113 ab, or concurrent registration in either.* 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 convective diffusion. Instructor: Kornfield.

ChE 104. Separation Processes. *9 units (3-0-6); third term. Prerequisite: ChE 63 ab.* An introduction to separation principles and processes. Physicochemical basis of separations. Precipitation, crystallization, filtration, extraction, distillation, fixed-bed adsorption, protein separations. Instructor: Arnold.

ChE 105. Process Control. *9 units (3-0-6); first term. Prerequisite: AMa 95 abc or AM 113 abc, or concurrent registration in either.* Review of Laplace transforms and linear algebra. Feedback control of linear systems. Frequency response. Sampled-data systems. Introduction to multivariable control. Instructor: Morari.

ChE 110 ab. Optimal Design of Chemical Systems. *12 units (3-0-9); 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. Instructors: Morari (a), Prater (b).

ChE 126 ab. Chemical Engineering Laboratory. *9 units (1-6-2); first, second terms.* Projects illustrative of problems in transport phenomena, unit operations, chemical kinetics, process control, and reactor design are performed. Instructors: Staff.

Ch/ChE 140. Special Topics in Chemistry and Chemical Engineering. Growth, Processing, and Characterization of Semiconductors and Semiconductor Interfaces. *6 units (2-0-4).* For course description, see Chemistry.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6).* For course description, see Chemistry.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6); third term. Prerequisites: Ch/ChE 147 or with instructor's permission.* An introduction to polymer physics, including thermodynamics of mixing, crystallization, rubber elasticity, melt rheology, rubber-glass transition, time-temperature superposition, and mechanical properties. Not offered 1990–91.

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 number; 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, including computation, will be developed and used throughout the course. Instructor: Brady.

ChE 151 c. Physical and Chemical Rate Processes. *12 units (3-0-9); third term.* Basic concepts in chemical kinetics and in analysis of multiple homogeneous reaction systems will be reviewed. Methods for kinetic description of very large sets of reactions, including polymerization processes, will be summarized. Kinetics and reactor engineering methods for heterogeneous reactions including catalytic, gas-liquid, and gas-solid reaction systems will be derived and applied. Associated mathematical methods and computational tools will be presented. Instructor: Bailey.

ChE/Env 157. Combustion and Air Pollution Sources. *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; the internal combustion engine; control techniques for particulate and gaseous pollutants. Not offered 1990–91.

ChE/Env 158. Air Pollution Aerosols. *9 units (3-0-6); first term. Open to graduate students and seniors with instructor's permission.* Fundamentals of particulate air pollutants; aerosol physics and chemistry; gas-to-particle conversion processes; pollutant effects on visibility. 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. Instructors: Staff.

ChE 163. Fundamentals of Biochemical Engineering. *9 units (3-0-6); second term. Prerequisite: ChE 101 or instructor's permission.* A first course in microbial and enzyme processes, natural or artificial, with applications to industrial fermentations, biocatalysis, and production of proteins using recombinant organisms. Topics: rudiments of microbiology; isolation and utilization of enzymes; kinetics of enzyme catalyzed reactions; substrate utilization and kinetics of microbial growth; microbial interactions in mixed cultures; transport phenomena in microbial systems; design and analysis of biological reactors. Instructors: Arnold, Bailey.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6); second term. Prerequisite: Ch 21 abc or equivalent.* Ensembles and statistical mechanical formulation of the laws of thermodynamics. Classical statistical mechanics; quantum statistics; translational, rotational, vibrational, and electronic partition functions. Chemical equilibria. Real gases and distribution functions; other interacting systems; liquids and solids. Instructor: Weitekamp.

ChE 165. Applied Chemical Thermodynamics. *9 units (3-0-6); first term. Prerequisite: ChE 63 abc or equivalent.* Review of first and second laws and engineering applications. Equations of state and thermodynamic properties of pure substances. Thermodynamics of gaseous and liquid mixtures. Theories of solutions. Phase and chemical equilibria. Instructor: Gavalas.

EE/ChE 170 ab. Control System Synthesis. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/ChE 171. Nonlinear Systems and Adaptive Control. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/ChE 172. System Identification and Estimation. *9 units (3-0-6).* For course description, see Electrical Engineering.

ChE 174. Special Topics in Transport Phenomena. *9 units (3-0-6); third term. Prerequisite: AM 113 or AMa 95, or concurrent registration in either, or instructor's permission.* 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; turbulence. Other topics may be discussed depending on class needs and interests. Instructor: Brady.

EE/ChE 175. Optimization and Optimal Control. *9 units (3-0-6).* For course description, see Electrical Engineering.

ChE 177. Protein Technology. *9 units (3-0-6); second term. Prerequisites: ChE 163, Ch/Bi 110 a, or instructor's permission.* A lecture and discussion course on selected topics in protein technology: protein engineering; enzyme kinetics; biocatalysis in unnatural environments; modern advances in protein separations: chromatography, extraction, genetic approaches to separations. Instructor: Arnold.

EE/ChE 270. Special Topics in Systems and Control. *9 units (3-0-6).* For course description, see Electrical Engineering.

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 2.

CHEMISTRY

Ch 1 abc. General Chemistry. *6 units (3-0-3); first, second, third terms.* 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, chemical equilibria. Second term: oxidation and reduction, systematics of reaction chemistry, theories of bonding, chemistry of the transition metals. Third term: special topics selected from contemporary chemical research emphasizing chemical reactivity, stereochemistry, and the characterization of molecules, biomacromolecules, solids, and surfaces. Graded pass/fail. Instructors: Gray, Lewis, Barton, Rees.

Ch 3 a. Fundamental Techniques of Experimental Chemistry. *6 units (0-6-0); 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: Chan and staff.

Ch 3 b. Experimental Procedures of Synthetic Chemistry. *8 units (1-6-1); third 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: Chan and staff.

Ch 4 ab. Synthesis and Analysis of Organic and Inorganic Compounds. *9 units (1-6-2); Prerequisite: Ch 1 abc (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 second terms; Ch 4 b, third term only. Instructors: Chan and staff.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. *9 units (1-6-2); first, second 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: Bercaw, Dougherty.

Ch 6 ab. Application of Physical Methods to Chemical Problems. *10 units (0-6-4); second, third terms. Prerequisites: Ch 1abc, 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 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. Instructor: Beauchamp.

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, or 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, introductory level. The other weekly session will acquaint students with the laboratory techniques and instrumentation used on the research topics. Ch 10 c is a research-oriented laboratory course, which will be supervised by a chemistry faculty member. Weekly class meetings will provide a forum for participants to discuss their research projects. Ch 10 c can be used as a substitute for Ch 1 c. Graded pass/fail. Instructors: Barton, Dervan, Lewis, Okumura.

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. Instructor: Richards.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); first term. Prerequisites: Ch 1 abc, 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 on determinations of chemical composition, measurement of equilibrium constants, and trace-metal analysis. Instructors: Anson, Rees.

Ch 21 abc. The Physical Description of Chemical Systems. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 abc, Ph 2 abc, Ma 2 abc.* Atomic and molecular quantum mechanics, spectroscopy, thermodynamics, statistical mechanics, and chemical kinetics. Instructors: Baldeschwieler, McKoy, Kuppermann.

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 abc.* 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. Instructor: Chan.

Ch 41 abc. Chemistry of Covalent Compounds. *9 units (3-0-6); first, second, third terms. Prerequisite: Ch 1 abc or instructor's permission.* The synthesis, structure, and mechanisms of reactions of covalent compounds. Emphasis will be on the study of molecules formed from carbon and other first- and second-row elements. Instructors: Grubbs, Imperiali.

Ch 80. Chemical Research. *Offered to B.S. candidates in chemistry. Prerequisite: consent of research supervisor.* Experimental and theoretical research experiment 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. *2 units (1-0-1); second term.* Training in the techniques of oral presentation of chemical topics. Practice in the effective organization and delivery of technical reports before groups. Graded pass/fail. Instructor: Parker.

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 1990–91.

Bi/Ch 110 abc. Biochemistry. *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. Instructor: Bercaw.

Ch 117. Introduction to Electrochemistry. *6 units (2-0-4); second term.* Discussion of the structure of electrode-electrolyte interface, the mechanism by which charge is transferred across it, and experimental techniques used to study electrode reactions. Topics change from year to year but usually include diffusion currents, polarography, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Not offered 1990–91.

Ch 118 ab. Experimental Electrochemistry. *Units by arrangement; third term.* Laboratory practice in the use of selected electrochemical instruments and techniques. The student may pursue a set of expository experiments or elect to carry out a research project in electrochemistry. Not offered 1990–91.

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. Prerequisite: Ch 21 a or an equivalent introduction to quantum mechanics.* Modern ideas of chemical bonding, with emphasis on qualitative concepts and how they are used to make predictions of geometries, energies, excited states, and rules for chemical reactions. Overview of methods for force fields and molecular dynamics simulations. Applications will emphasize molecules involving both main-group and transition metals and will include some discussion of impurity states in solids, and the bonding and reactions at surfaces of solids. Part c is a lab in which the student uses modern quantum chemistry computer programs to calculate wavefunctions and properties of molecules. Part b is not a prerequisite for part c. Instructor: Goddard.

Ch 122 ab. Methods for the Determination of the Structure of Molecules. *9 units (3-0-6); first, second 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 diffraction methods (first term) and nuclear magnetic resonance (second term). Instructors: Baldeschwieler, Schaefer.

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.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6).* For course description, see Geology.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6).* For course description, see Geology.

Ch 130 ab. Spectroscopy. *9 units (3-0-6); second, third terms.* 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 ab. Biophysics of Macromolecules. *9 units (3-0-6).* For course description, see Biology.

Ch 135. Chemical Dynamics. *9 units (3-0-6); third term. Prerequisites: Ch 21 abc and Ch 41 abc or equivalent, or consent of instructor.* Detailed considerations of cross sections, rates, energetics, and mechanisms of chemical reactions. Emphasis on theoretical models used to interpret gas-phase reactions studied with molecular beam and laser techniques. Instructor: Okumura.

Ch/ChE 140. Special Topics in Chemistry and Chemical Engineering. Growth, Processing, and Characterization of Semiconductors and Semiconductor Interfaces. *6 units (2-0-4); third term.* The growth of different classes of semiconductors, including Group IV elements and both III-V and II-VI compound semiconductors. Emphasis will be on current techniques, such as Molecular Beam Epitaxy, Chemical Vapor Deposition, Metal-Organic Chemical Vapor Deposition, Liquid Phase Epitaxy, and Vapor Phase Epitaxy and how they can be used to grow multilayer structures. Electrical, physical, and chemical characterization of materials grown via these processes will be examined, with emphasis on surface-sensitive techniques. Factors influencing semiconductor interface properties will be explored in detail. Other topics include laser-assisted processes, metallization, and etching techniques. Not offered 1990–91.

Ch 142. Frontiers in Chemical Biology. *4 units (2-0-2); second term. Prerequisite: Bi/Ch 110 abc or instructor's permission.* A discussion of enzyme structure and function, and ligand-protein-nucleic acid interactions. Not offered 1990–91.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); first, second terms. 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; third term: organic polymeric substances; structure, properties, synthesis, and uses. Instructors: Dougherty, Myers.

Ch 145. Bioorganic Chemistry of Proteins. *9 units (3-0-6); first term. Prerequisites: Ch 41 abc and Bi/Ch 110 a.* 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. Given in alternate years; not offered 1990–91. Instructor: Imperiali.

Ch 146. Bioorganic Chemistry of Nucleic Acids. *9 units (3-0-6); second 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, oligonucleotide-directed triple helical formation; RNA structure and RNA as catalysts (ribozymes) will be discussed. Given in alternate years; offered 1990–91. Instructor: Dervan.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 41 abc.* An introduction to the chemistry of polymers including synthetic methods, mechanisms, and kinetics of macromolecule formation, and characterization techniques. Instructor: Grubbs.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 154. Organometallic Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 112 or equivalent.* A general discussion of the reaction mechanisms, synthetic and catalytic uses of transition metal organometallic compounds. Instructor: Labinger.

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. Not offered 1990–91. Instructor: Marcus.

Env/Ch/Ge 175 ab. Environmental 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 ab. Advanced Inorganic Chemistry. *9 units (2-0-7); second, third terms. Prerequisites: Ch 112 and Ch 21 abc or concurrent registration.* Topics in modern inorganic chemistry. Second term: inorganic photochemistry. Third term: bioinorganic chemistry. Instructors: Barton, Gray.

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 224. Advanced Topics in Magnetic Resonance. *9 units (2-0-7); second 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. Not offered 1990–91. Instructor: Weitekamp.

Ch 227 ab. Advanced Topics in Chemical Physics. *9 units (3-0-6); second, third terms. 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 1990–91.

Ch 229 abc. Experimental Basics of X-Ray Diffraction. *6 units (2-0-4); first, second, third terms.* First term: production, collimation, and monochromatization of x-rays, including total reflection, refraction, and polarization; second term: detection, energy analysis, and intensity measurements of x-rays, including theory and practice of diverse counting techniques; third term: basics of x-ray instrumentation, including metrology of complex multi-axis systems and the pertinent principles of heat-transfer as applied to very accurate cryogenic x-ray analysis of single crystals. Not offered 1990–91.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4); second 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. Offered in 1990–91 and alternate years. Instructor: Parker.

Ch 241 a. Topics in Advanced Organic Chemistry. *6 units (2-0-4); second term. Prerequisite: Ch 41 abc.* In 1990–91, will cover NMR and FT-NMR basics and applications, with emphasis on those techniques used in structural analysis, including decoupling, NOSEY, and COSY. Extensive practice in the use of these techniques will be available with the highly interactive Chapman-Russell *FT NMR Problems* video-disk-based computer program which features on-screen spectra at a variety of magnetic fields with, and without, decoupling, and so on. The practical use of NMR to determine reaction rates and conformational equilibration will be described, as will applications of NMR to imaging and spectroscopy of living systems. Instructor: Roberts.

Ch 242 a. Chemical Synthesis. *9 units (3-0-6); first term. Prerequisite: Ch 41 abc.* An integrated approach to synthetic problem solving featuring an extensive review of modern synthetic reactions with concurrent development of general strategies for synthesis design. Instructor: Myers.

Ch 244 a. Topics in Chemical Biology. *6 units (3-0-3); first term.* A discussion of biological membrane biogenesis, structure, and function. Topics range from membrane-bound enzymes to receptors for neurotransmitters, hormones, light, proteins, or peptides, and will include current work on models of simple behavior. Not offered 1990–91.

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 1990–91.

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 10 abc. Structural Analysis and Design. *9 units (3-0-6); first, second, third terms. Prerequisite: AM 97 abc.* Study and design of selected structures such as a reinforced concrete building, arch bridge, gravity dam, or engineering facility. Each project considers initial conception, cost-benefit, and optimum design, and concludes with actual design of a structure or portion of a structure. Not offered 1990–91.

CE 17. Civil Engineering. *9 units (3-0-6); third term. Prerequisite: senior standing.* Selected comprehensive problems of civil engineering systems involving a wide variety of interrelated factors. Not offered 1990–91.

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.

CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 19 abc or equivalent; AMa 95 abc or AM 113 abc or 114 abc (may be taken concurrently).* General equations of fluid motion; two- and three-dimensional steady and *nonsteady* potential motion; cavity and wake flow; surface waves, linear and *nonlinear* shallow-water waves, flow in stratified fluids, stability; acoustic fields, sound radiation and scattering, acoustic energy transport; one-dimensional steady and *nonsteady* gasdynamics, expansion fans, shock waves; two- and three-dimensional flow fields; laminar flow, Stokes and Oseen problems, laminar boundary layer; laminar instability, turbulent shear flow; introduction to selected special problems in heterogeneous flow, chemically reacting flow, sediment transport, flow through porous media. Instructors: Staff.

CE 105. Introduction to Soil Mechanics. *9 units (2-3-4); first term. Prerequisite: AM 97.* A general introduction to the physical and engineering properties of soil, including origin, classification and identification methods, permeability, seepage, consolidation, settlement, slope stability, lateral pressures and bearing capacity of footings. Standard laboratory soil tests will be performed. Instructor: Scott.

CE 110. Analysis and Design of Hydraulic Projects. *6 or more units as arranged; any term.* 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 111. 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 undergraduates, it is also open to first-year graduate students who have not had an equivalent course. Instructor: Raichlen.

CE 113 ab. Coastal Engineering. *9 units (3-0-6); first, second terms. Prerequisites: ME 19 abc and CE 111 or equivalents; AMa 95 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. Not offered 1990–91.

CE 115 ab. Soil Mechanics. *9 units (3-0-6); first term. 9 units (2-3-4); second term. Prerequisite: CE 105 or equivalent; may be taken concurrently.* 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. Instructor: Scott.

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. Graded pass/fail. Instructors: 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. Instructor: Scott.

CE 160 abc. Structural Engineering. *9 units (3-0-6); first, second, third terms. Prerequisite: CE 10 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. Not offered 1990–91.

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. Instructors: Staff.

CE 181. Principles of Earthquake Engineering. *9 units (3-0-6); first 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. Not offered 1990–91.

CE 182. Structural Dynamics of Earthquake Engineering. *9 units (3-0-6); second term. Prerequisite: AM 151 ab.* Response of structures to earthquake ground motion; nature of building code requirements and their relation to actual behavior of structures such as long-span suspension bridges, and fluids in tanks and reservoirs; earthquake design criteria. Not offered 1990–91.

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: AMa 95 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 1990–91.

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, structural forces due to waves, tsunamis, and other impulsive wave systems. Not offered 1990–91.

CE 300. Civil Engineering Research.

For courses in environmental engineering science and hydraulics, see those sections.

COMPUTATION AND NEURAL SYSTEMS

CNS/EE 124 ab. Pattern Recognition. *9 units (3-0-6); second, third terms. Prerequisite: Ma 2.* Covers classic results from pattern recognition and discusses in this context associative memories and related neural network models of computation. Discriminant functions, capacity of linear discriminant functions, perceptron and related teaching algorithms, parametric (statistical) training techniques, unsupervised learning; nonlinear discriminant functions, associative memories, learning algorithms for layers of discriminant functions. Instructor: Psaltis.

APh/CNS/EE 133. Optical Computing. *9 units (3-0-6).* For course description, see Applied Physics.

CS/CNS 174 abc. Computer Graphics Laboratory. *9 units (3-3-3).* For course description, see Computer Science.

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 pre-candidacy students.*

CNS/CS/EE 182 abc. Analog Integrated Circuit Design. *9 units (3-3-3); first, second, third terms. Prerequisites: EE 14, EE 90, APh 3, CS 10, or their equivalents.* Device, circuit, and system techniques for designing large-scale CMOS analog systems. MOS transistor above and below threshold; current mirrors; differential transconductance amplifier; analog addition, subtraction, multiplication, absolute value, interpolation division. Circuits with time constants: linear filters of first and second order, monostable and astable relaxation oscillators. Automatic gain and control system examples from feedback control, vision, and auditory processing. In addition to laboratory work on elementary circuits, each student will design a modest system-level project and submit it for fabrication. Third-term laboratory is reserved for testing and evaluating these projects. Instructor: Mead.

CNS/CS/EE 184 abc. Analog Integrated Circuit Projects Laboratory. *Units by arrangement; second, third, first terms. Prerequisite: CNS 182 abc; may be taken concurrently with CNS 182 bc.* Design projects in large-scale analog integrated systems. Each student, or pair of students, is expected to define, design, verify, and submit for fabrication a system of their choice. The project definition and simulation must be finished by the end of the second quarter (184a), and the final design must be verified and submitted for fabrication by the end of the third quarter (184b). Testing and characterization of the fabricated circuits will be done in the first quarter of the following year (184c). A two-term version of the course can be made available by arrangement with the instructor. Graded on a pass/fail basis. Instructor: Mead.

CNS/Bi/Ph 185. Collective Computation. *9 units (3-0-6); 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, analog decoding, combinatorial problems, sequences; neural nets for speech and image processing; systems that learn; self-organizing maps. Course work will include a short hardware or software project. Instructor: Hopfield.

CNS/Bi 186. Vision: From Computational Theory to Neuronal Mechanisms. *9 units (4-0-5); second term. Prerequisites: Bi 150 or instructor's consent.* Lecture and discussion course aimed at understanding visual information processing in both biological and artificial systems. The course will emphasize an interdisciplinary approach aimed at understanding vision from several levels: computational theory, algorithms, psychophysics, and a study of the hardware (neurophysiology and/or circuit theory). Consideration will be given to a number of distinct processes in early vision (e.g., binocular stereo, motion analysis, edge detection, color). Students will be required to complete one project (mathematical analysis, computer modeling, psychophysics, or hardware implementation). Instructors: Koch and Van Essen.

CNS 221. Computational Neurobiology. *9 units (4-0-5); third term. Prerequisites: Bi 150, CNS 185; or instructor's consent.* Lecture, discussion, and laboratory aimed at understanding computational aspects of information processing within the nervous system. 1990–91: Methods in Computational Neuroscience. The course will teach how to simulate neuronal structures at various scales, from extracting the relevant neurobiological data to computer modeling. Single channel models; compartmental models; calcium dynamics; small invertebrate model systems; visual and olfactory systems in mammals; connectionist networks; numerical solutions of differential equations; electronic circuit simulators; graphical tools; numerical versus analytical approaches; neural networks; and parallel computers. Students are expected to complete one simulation project on the Neural Network Simulator in the CNS lab. Instructors: Bower and Koch.

CNS 256. Methods of Multineural Recording. *6 units (2-0-4); third term. Prerequisite: Bi/Ph 50 or Bi 150.* Reading and discussion course, topics to include multielectrode recording *in vitro* and *in vivo*; optical detection of activity; event-related electric potentials and magnetic fields; activity-related measures using 2-deoxyglucose autoradiography and positron emission tomography. Engineering aspects as well as underlying biophysics will be studied. Given in alternate years. Instructor: Pine.

CNS 280. Research in Computation and Neural Systems. *Hours and units by arrangement. For graduate students admitted to candidacy in computation and neural systems.*

COMPUTER SCIENCE

CS/EE 4. Introduction to Digital Electronics. *6 units (2-0-4); first term.* An introduction to modern digital design techniques. Boolean algebra and the formulation of logic equations. Hardware realization of combinational and sequential logic circuits. The building blocks and operation of a computer: binary arithmetic, the ALU, and random-access memory. Graded pass/fail. Instructor: Goodman.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6).* For course description, see Mathematics.

CS 10. Introduction to Programming. *6 units (1-4-1); first, second terms.* Structured programming methods and high-level programming. Control structures, data manipulation, elementary data structures, recursion, and interactive graphical input and output. Weekly laboratory exercises programming personal computers in PASCAL. Instructors: Staff.

CS/EE 11. Digital Electronics Laboratory. *6 units (0-3-3); second term. Prerequisites: CS/EE 4. 6 units credit allowed toward freshman laboratory requirement.* An introductory laboratory designed to provide practical hardware experience of theory covered in CS/EE 4. The student is expected to design, build, and test a wide variety of commonly used digital circuits using modern integrated circuits. Graded pass/fail. Instructor: Goodman.

CS 12. Introduction to Data Structures and Algorithms. *9 units (2-4-3); third term. Prerequisite: CS 10 or equivalent.* Problem solving, top-down program design, and invariants. Time and space complexity of algorithms. Data structures including stacks, queues, heaps, priority queues, and trees. Sorting, searching, and hashing methods. The laboratory involves several small programming exercises followed by an assigned project. Instructors: Staff.

CS 20 abc. Computation, Computers, and Programs. *9 units (3-3-3); first, second, third terms. Prerequisite: CS 12 or equivalent.* An introduction to computation and computing science. The representation and implementation of computations as programs and machines. Relationships between physical computing machines and abstract processes. Representation of data. Abstraction and composition. Algorithms, complexity, and efficiency. Limitations of computations. Correctness concerns. Nondeterminism. Unification. Reversible computations. Design of computers and programs. Laboratory work using UNIX workstation computers to explore computations and programs. Instructor: van de Snepscheut.

CS 51. Principles of Microprocessor Systems. *9 units (3-0-6); first term. Prerequisite: CS/EE 4 or permission of instructor.* The principles and design of microprocessor-based computers. Subjects include switching theory, minimization of switching functions, computer arithmetic, machine models, and assembly language programming. Instructor: Ray.

CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0); second term. Prerequisite: 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 modern development facilities and standard design techniques. Instructor: Ray.

CS/EE 53. Microprocessor Project Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor; third term. Prerequisite: CS 52 or equivalent.* A project laboratory to permit the student to select, design, and build a microprocessor system. Instructor: Ray.

CS/EE 54. Advanced Microprocessor Projects Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor; first term. Prerequisite: permission of instructor.* A project laboratory to permit the student to design and build a microprocessor-based system. This laboratory is for the experienced student who can work independently and who has taken or has had experience equivalent to CS/EE 53. Instructor: Ray.

CS 80 abc. Undergraduate Research in Computer Science. *Units in accordance with work accomplished. Consent of both research adviser and course supervisor required before registering.* Supervised research in computer science by undergraduates. Topic must be approved by the supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructors: Staff.

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, second, third terms. Prerequisites: Ma 2 c and CS/EE 4 or equivalent.* A basic course in information theory and computational complexity with emphasis on fundamental concepts and tools that equip the student for research in these areas. Topics include Shannon's theory, Turing machines and computability, Kolmogorov complexity, information flow in computation, time and circuit complexity, VLSI complexity, and collective computation. A unified analytic approach will be followed throughout, and the theory will be interpreted through practical applications. Not offered 1990–91.

AMa/CS 132 abc. Concurrent Scientific Computing. *9 units (3-3-3).* For course description, see Applied Mathematics.

CS 138 abc. Computer Algorithms. *9 units (3-0-6); first, second, third terms. Prerequisite: CS 12 or equivalent.* Design, analysis, and proofs of correctness of computer programs. Program specification, methods of proving program correctness, and computational complexity. NP-completeness. Models of parallel, concurrent, and distributed computation. Searching, sorting, string matching. Graph, geometric, algebraic, and matrix algorithms. Linear programming. Heuristic search. Discrete-event simulation. Algorithms for distributed systems. Part of the third term is spent studying applications in one branch of science or engineering. The topic for 1990–91 is applications in biology. Instructor: Chandy.

CS 139 ab. Concurrency in Computation. *9 units (3-0-6); first, second 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. Not offered 1990–91.

CS 140 ab. Programming Laboratory. *9 units (3-4-2); second, third terms. Prerequisite: CS 12 or equivalent.* An introduction to object-oriented, functional, and logic programming, with laboratory exercises and a full-scale project. Each of these programming paradigms affords its own benefits in particular application domains. C++ and Cosmic C will be used to explore object-oriented and communicating-process programming, Lisp and Scheme to explore functional programming, and Prolog and Strand to explore logic programming. The second term of the course gives students the opportunity to develop, under close guidance, a programming project whose complexity is at the scale of a compiler, using one of the paradigms presented in the first term. The emphasis in the project is not only in achieving the task, but presenting a clear problem specification, a modular design, and a maintainable implementation. Instructor: Taylor.

CS 142 abc. Decision Support Systems. *9 units (3-3-3); first, second, third terms. Prerequisite: CS 10 or programming experience using PASCAL.* The building of conceptual models as an expression of the patterns perceived in the analysis of data. Data base systems, discrete simulation, decision support systems, and expert systems. Small group projects and extensive use of the computer. Instructor: Thompson.

CS 144 abc. Artificial Intelligence. *9 units (3-3-3); first, second, third terms. Prerequisite: consent of instructor.* Current areas of research in artificial intelligence, including knowledge representation, expert systems, natural language understanding, inference and reasoning, and theorem proving. In the first two terms, individual or small group projects will be required; a class project will be a major part of third term. Not offered 1990–91.

CS 170 abc. Computer-Aided Design. *9 units (3-0-6); first, second, third terms.* An overall view of computer subsystem design flow in practice, and of required computer design aids: design languages and representations; design data bases and data structures; topological, geometrical, and electrical models; algorithmic and analytic techniques for partitioning; design verification, simulation, testing, checking, and layout. Incorporation of programs into computer-aided design systems. A principal goal of the course is the specification, design, carrying out, and documentation of portions of an actual design system, with the student working as a member of a design team. Instructor: Ayres.

CS/CNS 174 abc. Computer Graphics Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisites: Ma 2, CS 10, and extensive programming experience.* The art of making pictures by computer. Hardware and algorithms will be described. Topics: graphics input and output, three-dimensional transformations and interactive modeling, physically based modeling, surface rendering, ray tracing, and lighting models. Students will implement several medium-scale projects; there will be an opportunity for independent projects third term. Instructor: Barr.

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. Prerequisites: CS/EE 4 and CS 10, or equivalent.* 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: Seitz.

CNS/CS/EE 182 abc. Analog Integrated Circuit Design. *9 units (3-3-3).* For course description, see Computation and Neural Systems.

EE/CS 183 abc. Integrated Digital Communication. *9 units (3-0-6).* For course description, see Electrical Engineering.

CNS/CS/EE 184 abc. Analog Integrated Circuit Projects Laboratory. *Units by arrangement.* For course description, see Computation and Neural Systems.

CS 185 ab. Design of Asynchronous VLSI Circuits. *9 units (3-3-3); first, second terms. Prerequisites: CS 139 and CS/EE 181 (may be taken concurrently).* 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.

CS 237 abc. Design and Implementation of Programming Languages. *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. Not offered 1990–91.

CS 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.

CS 274 abc. Advanced Topics in Computer Graphics. *9 units (3-3-3); first, second, third terms. Prerequisite: CS 174, or permission of instructor.* The emphasis of this course is to gain understanding of the theoretical foundations underlying techniques used in computer graphics. The topics treated vary from year to year. Typical past and future topics: differential geometry, probability, stochastic processes and Monte Carlo, differential topology, algebraic geometry. May be repeated for credit with permission of instructor. Not offered 1990–91.

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. Special Topics in Computer Science. *9 units (3-0-6). Permission of the instructor required.*

CS 286 abc. Seminar in Computer Science. *9 units (3-0-6). Permission of the instructor required.*

ECONOMICS

Ec 11. Introduction to Economics. *9 units (3-0-6); first, second terms.* An introduction to economic methodology, models, and institutions. Includes both basic microeconomics and an introduction to modern approaches to macroeconomic issues. Instructors: Border, Plott.

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 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).* Instructors: Staff, visiting lecturers.

Ec 112. History of Economic Analysis. *9 units (3-0-6). Prerequisite: Ec 11 or SS 13.* History of the development of economic doctrine and theory. Specific periods of emphasis may vary with instructor. Instructors: Border, El-Gamal, Hoffman.

Ec 114. Economics of Crime. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* This course studies the economic approach to criminal behavior and its application to various related policy issues, such as the deterrent effects of capital punishment, the optimal allocation of social resources to law enforcement, and tax evasion. Both theoretical and empirical analyses will be utilized. Instructor: Wilde.

Ec 116. Contemporary Socioeconomic Problems. *9 units (3-0-6); second term. Prerequisites: Ec 11 and PS/SS 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: Wilde.

Ec 118. Environmental Economics. *9 units (3-0-6); third term. 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. Instructors: Staff.

Ec 120. International Economic Theory. *9 units (3-0-6); third term.* Factors affecting the exchange of goods and services and the flow of capital between markets. Theory is stressed. Instructors: Staff.

Ec 121 ab. Theory of Value. *9 units (3-0-6); first, second terms. Prerequisites: Ec 11 and PS/SS 12 or equivalents.* A study of consumer preference, the structure and conduct of markets, factor pricing, measures of economic efficiency, and the interdependence of markets in reaching a general equilibrium. Instructors: Staff.

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. Instructors: Dubin, McKelvey.

Ec 123. Forecasting Economics Time Series. *9 units (3-0-6); third term. Prerequisite: Ec 122.* Various forecasting techniques; application to business and economics. Instructors: Staff.

Ec 124 abc. Mathematical Methods of Economics. *9 units (3-0-6). Prerequisites: Ma 107 and Ec 121 ab (can be taken concurrently).* Mathematical tools of modern economic theory and their applications to consumer theory, general equilibrium, and welfare economics. Emphasis on developing rigorous exposition by the students. Instructors: Staff.

Ec 125 ab. The Economics of International Relations. *9 units (3-0-6); first, second terms.* Economic and political factors influencing relations among nations. Topics: foreign exchange markets, international banking and business, the pattern of international trade and payments, the International Monetary Fund and the World Bank, the European Common Market, and the American Foreign Aid Program. The foreign economic policy of the U.S. is analyzed in some detail. This course emphasizes theory less than does Ec 120. Instructors: Staff.

Ec 127. Problems in Economic Theory (Seminar). *Units by arrangement; first, second, third terms. Prerequisite: Ec 121.* Consideration of selected topics in economic theory. Instructors: Staff and guest lecturers.

Ec 128. Economic Growth in Historical Context. *9 units (3-0-6). Prerequisite: Ec 11 or SS 13.* Analyzes and compares the growth of per capita product in the developed world since 1750; and, in that context, the problems of economic development in the third world today will be introduced. Instructor: Davis.

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 130. Economic History of Europe Since the Late Middle Ages. *9 units (3-0-6). Prerequisite: Ec 11 or SS 13.* Employs the theoretical and quantitative techniques of economics to help explore and explain the development of the European cultural area between 1500 and 1950. Topics include the rise of commerce, the industrial revolution, the demographic transition, and imperialism. Instructors: Davis, 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: Wilde.

Ec/PS 134. The Political Economy of Urban Areas. *9 units (3-0-6); first term. Prerequisite: PS/SS 12 or equivalent.* Development of a theory of urban government, using analytic concepts from microeconomics and political science. Instructor: Kiewiet.

Ec 135. Economics of Uncertainty. *9 units (3-0-6). Prerequisite: Ec 11, Ma 2.* An analysis of the effects of uncertainty 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, value of information, and equilibrium. Instructor: Palfrey.

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. Instructor: Border.

Ec 140. Economics of Energy Policy. *9 units (3-0-6); third term. Prerequisite: Ec 121 ab or equivalent.* Issues in contemporary resource/energy policies with particular emphasis on federal energy independence policy. After a brief survey in theory of resource economics, major issues are identified and their current solutions are contrasted to other alternatives in terms of feasibility and optimality. Instructor: Dubin.

Ec 143. Resource Economics. *9 units (3-0-6); first term. Prerequisite: Ec 11.* Topics in the allocation of natural resources. Problems of extraction, exploitation, exploration, etc., for renewable and nonrenewable resources, e.g., fisheries, fresh water, fossil fuels. Instructor: Palfrey.

Ec/SS 145. Public Finance. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Instructor: Ledyard.

Ec/Pl 147. Altruism and Fairness in Economics.* *9 units (3-0-6). Prerequisite: Ec 11.* A study and discussion of altruism and fairness and their congruence with standard economic models. Philosophical theories of justice and fairness will be compared with the treatment of these notions within economics. The emphasis will be on class discussion and short papers or problems. Instructors: Ledyard, Woodward.

Ec 150. Chaotic Dynamics in Economic Systems. *9 units (3-0-6); first term. Prerequisites: Ma 2, Ma 112.* Nonlinear difference equations arising in partial equilibrium, Keynesian, and capital theoretic models; analysis of symbolic dynamics, periodicity, topological chaos, and ergodicity; numerical and statistical issues of estimation, hypothesis testing, and Monte Carlo experiments. Instructor: El-Gamal.

Ec 161. Business Cycles. *9 units (3-0-6); second 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. Instructor: Hughson.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement.* *See page 105.*

Ec 162. Monetary Theory. *9 units (3-0-6); third term. Prerequisites: Ec 11, Ec 122.* 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: Dubin.

ELECTRICAL ENGINEERING

CS/EE 4. Introduction to Digital Electronics. *6 units (2-0-4).* For course description, see Computer Science.

CS/EE 11. Digital Electronics Laboratory. *6 units (0-3-3).* For course description, see Computer Science.

EE 14 abc. Introduction to Electronic Engineering and Laboratory. *12 units (3-2-7); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Linear circuit analysis, Kirchhoff's laws, transient and steady-state network solutions, phasors, Thevenin and Norton theorems, Bode plot, power transfer, resonant circuits. Device physics of diodes, FETs, and bipolar transistors, device characteristics, models, limitations. Transistor bias circuits, multi-transistor circuits, current mirrors, cascodes. Digital circuit analysis, DTL, TTL, ECL, MOS logic circuits. Analog circuit analysis, small signal analysis, amplifiers, frequency response. Operational amplifiers, Op-amp circuit analysis, Op-amp applications. Feedback circuits, stability, Nyquist's theorem. Distributed circuits, transmission lines, transients, sinusoidal excitation, loss, phase velocity, directional coupling. Laboratory experiments are designed to match course materials. Instructors: Tai, Bridges, Goodman.

EE 32 ab. Introduction to Linear Systems. *9 units (3-0-6); first, second terms. Prerequisites: Ma 1, Ma 2, and EE 14.* 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). Instructors: Abu-Mostafa, Doyle.

EE 40. Fundamentals of Energy Processing Systems. *9 units (3-0-6); first term. Prerequisites: Ma 2 abc, Ph 2 abc, EE 14 abc, EE 90 abc.* Introduction to electrical energy processing systems as distinct from information processing systems. Elementary magnetic devices: generators, motors, and transformers. The special problems of electronic power processing. Instructor: Cuk.

CS/EE 53. Microprocessor Project Laboratory. *9 units (0-9-0) or 12 units (0-12-0) as arranged with the instructor.* For course description, see Computer Science.

CS/EE 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 Computer Science.

EE 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research experience, open only to senior electrical engineering majors. Requirements set by individual faculty members include a written report based on actual laboratory experience. Topic selection and final report must be approved by the Electrical Engineering Undergraduate Committee. Not offered on pass/fail basis. Instructors: Staff.

EE 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research experience, open only to senior electrical engineering majors. Requirements set by individual faculty members include a written report based on work performed. Topic selection and final report must be approved by the Electrical Engineering Undergraduate Committee. Not offered on pass/fail basis. Cannot be used to satisfy the laboratory requirement in EE. Instructors: Staff.

EE 91 abc. Experimental Projects in Electronic Circuits. *Units by arrangement; 6 units minimum each term. Prerequisites: EE 14 abc and EE 90 or equivalents. Recommended: EE 114 abc or CS 112, 114, 116 (may be taken concurrently). Open to seniors; others only with consent of instructor.* An opportunity to do original projects in electronics and electronic circuits. Selection of significant projects, the engineering approach, demonstration of a finished product through the use of modern electronic techniques. The use of integrated circuit elements, digital and analog, is encouraged. Printed circuit board facilities are available. Text: Literature references. Instructor: Goodman.

EE/Mu 107 abc. Projects in Music and Science. *Units to be individually arranged, up to a maximum of 9.* 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 and 107 a as prerequisites.* Credit in music or EE but not in both. Instructor: Boyk.

EE 112 ab. Digital Signal Processing Principles. *9 units (3-0-6); first and second terms. Prerequisites: EE 32 ab and AMa 95 abc or equivalents.* Advanced discrete-time linear systems concepts, stability-test procedures, DFTs and Fast Fourier Transforms, FIR and IIR digital filter design and implementation, structural passivity and losslessness with applications to low round-off noise, low sensitivity and limit-cycle free structures, digital signal processing structures suitable for VLSI implementation, periodically time varying systems, multirate concepts including block filtering, quadrature mirror filtering, and unconventional sampling theorems. Instructor: Vaidyanathan.

EE 114 abc. Electronic Circuit Design. *9 units (3-0-6); first, second, third terms. Prerequisite: EE 14 abc or equivalent.* Applications of solid-state electronic devices in circuits and systems. Emphasis on methods of engineering analysis and design. Recommended for seniors and graduate students. Instructor: Middlebrook.

EE 117 ab. Power Electronics. *9 units (3-1-5) second term; (3-2-4) third term. Prerequisite: EE 14 abc or equivalent.* Introduction to repetitively switched power circuits for ac-to-dc, dc-to-ac, and dc-to-dc conversion and/or regulation of voltage or current in high-power applications: power supplies, motor controls, power amplifiers. Components, control techniques, analysis, and design. Laboratory part of the course includes the design of a switching dc-to-dc converter (part a), closed loop regulator (part b), and verification of the analysis technique and measurement methods through the laboratory assignments (part b). Instructor: Cuk.

CNS/EE 124 ab. Pattern Recognition. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

EE/Ma 126. Information Theory. *9 units (3-0-6); first term. Prerequisite: Ma 2 abc.* Shannon's mathematical theory of communication. Entropy and mutual information for discrete and continuous random variables; mathematical models for communication channels; Shannon's noisy-channel coding theorem; calculation of channel capacity. Discussion of the implications of the theory for real communication systems. This course, when followed by EE/Ma 127 ab (for which, however, it is not a prerequisite), should prepare the student for research in information and coding theory. Instructor: McEliece.

EE/Ma 127 ab. Error-Correcting Codes. *9 units (3-0-6); second, third terms. Prerequisite: Ma 2 abc.* This course, which is a sequel to EE/Ma 126, but which may be taken independently, will cover the most important techniques for combating errors that occur in the transmission or storage of data. Topics: algebraic block codes, e.g., Hamming, Golay, BCH, Reed-Solomon, Goppa, Fire; convolutional codes; concatenated codes; and the associated encoding and decoding algorithms. Self-contained introduction to the theory of finite fields. Instructor: Pollara.

EE 128. Multirate Signal Processing. *9 units (3-0-6); third term. Prerequisite: EE 32 ab, AMa 95 abc, or equivalent.* Course deals with multirate signals and systems. Instead of a single sampling rate, as in conventional systems, multiple sampling rates are involved in these systems. Applications of such systems include speech and image coding, voice privacy systems, signals and system coding, and system optimization. Topics: periodically time-varying systems, bifrequency descriptions, decimation and interpolation filters, quadrature mirror filter banks, unconventional sampling theorems, multirate adaptive filters, and error-free signal reconstruction. Instructor: Vaidyanathan.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6).* For course description, see Computer Science.

APh/EE 130. Introduction to Optoelectronics. *9 units (3-0-6).* For course description, see Applied Physics.

APh/EE 131. 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.

APh/CNS/EE 133. Optical Computing. *9 units (3-0-6).* For course description, see Applied Physics.

Ay/EE 144. Synthetic Imaging by Interferometers: Radio, Infrared, and Optical. *9 units (3-0-6).* For course description, see Astronomy.

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); second term. Prerequisite: EE 14.* Foundations of circuit theory. Transmission lines, statics, Maxwell's equations, and plane waves. Instructor: Rutledge.

EE 152. Guided Wave Circuits. *12 units (3-2-7); second term. Prerequisite: EE 151 or equivalent.* Wave propagation in metal waveguides and dielectric waveguides; optical fibers, integrated circuits, and applications to opto-electronic systems. Selections from periodic propagating structures, and coupled mode devices. Instructor: Bridges.

EE 153. Microwave Engineering. *12 units (3-2-7); first term. Prerequisite: EE 151.* Computer-aided design, fabrication, and network-analyzer measurements of very high-speed circuits and antennas. Filters, directional couplers, high-speed transistor models, low-noise amplifiers, oscillators, injection locking, Schottky-diode detectors, patch antennas, and arrays. Instructor: Rutledge.

EE/Ge 157 abc. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 2 abc 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. A brief introduction to image processing procedures in the third term. 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, data, and radar. Instructor: McEliece.

EE 162. Random Processes for Communication and Signal Processing. *9 units (3-0-6); first term. Prerequisite: Ma 100 or equivalent.* Introduction to single parameter random processes: stationarity; correlation functions; power spectral density; Gaussian processes. Response of linear systems to random processes. Least mean square error linear filtering and prediction. Instructor: Simon.

EE 163 ab. Communication Theory. *9 units (3-0-6); second, third terms. Prerequisite: EE 162 or equivalent.* 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 analog and digital baseband and carrier communication systems. Instructor: Simon.

EE 164. Adaptive Filters, Linear Prediction, and Optimal Filters. *9 units (3-0-6); third term. Prerequisites: EE 112 ab 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 sub-bands, 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 cancelation, interference minimization, and antenna arrays. Not offered 1990–91.

EE 165. Topics in Telecommunication System Engineering. *9 units (3-0-6); third term. Prerequisite: at least one term of communications or signal processing. For students having some familiarity with telecommunication elements and models.* Approaches to the design of overall telecommunication systems based on specifications, constraints, and demand. Topics will be chosen from terrestrial, satellite, and deep space communication, radar and radio navigation, and switched voice and data networks ranging in size from the office to the world. Topics and examples depend on instructor's and students' interests. Instructors: Staff.

EE/ChE 170 ab. Control System Synthesis. *9 units (3-0-6); second, third terms. Prerequisite: E/ChE 102 or equivalent. May be taken concurrently.* Matrix fraction descriptions (MFDs) of linear systems. Spectral factorization and Riccati equations. Wiener-Hopf optimal control. Linear quadratic (LQ) optimal control, robustness and other properties of LQ regulators, and stochastic optimal control. H_∞ optimal control. Design projects involving simulation and experiments. Instructors: Doyle, Morari.

EE/ChE 171. Nonlinear Systems and Adaptive Control. *9 units (3-0-6); second term. Prerequisite: E 102 or equivalent.* Methods for analysis and design of nonlinear control systems emphasizing Lyapunov theory. Model reference adaptive control, self-tuning regulators, instability mechanisms, universal stabilizers, and robustness of adaptive control schemes. Instructors: Staff.

EE/ChE 172. System Identification and Estimation. *9 units (3-0-6); first term. Prerequisite: E/ChE 102 a, E 162, or equivalent. May be taken concurrently.* Review of probability, statistics, and random processes. Parametric and nonparametric identification, spectral analysis, least squares, maximum likelihood estimation, optimal filtering, and prediction. Instructors: Staff.

EE/ChE 175. Optimization and Optimal Control. *9 units (3-0-6); first term. Prerequisite: E/ChE 102 a. May be taken concurrently.* Linear and nonlinear programming. Optimization of dynamic systems, variational methods, and dynamic programming. Instructor: Doyle.

EE/APh 180. Solid-State Devices. *9 units (3-0-6); third term. Prerequisite: EE 151 or Ph 106 (may be taken concurrently).* With the phenomenological statement of physical principles, the performance of a device and its representation in terms of an equivalent circuit is derived from 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, and the field-effect transistor. Instructor: Nicolet.

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

CNS/CS/EE 182 abc. Analog Integrated Circuit Design. *9 units (3-3-3).* For course description, see Computation and Neural Systems.

EE/CS 183 abc. Integrated Digital Communication. *9 units (3-0-6); first, second, third terms. Prerequisite: At least one term of communications or signal processing.* Concepts and systems used in digitally transmitting, synchronizing, and switching voice, data, and images in communication networks, with emphasis on common-carrier and computer communication networks. Digital representation, multiplexing, traffic theory, queueing theory, circuit switching, protocol hierarchy, packet switching, local area networks, integrated services, cellular radio, and analysis and design of large-scale circuit switches and switched digital networks. Emphasis is on the changes in communication concepts being wrought by the digital revolution. Instructor: Posner.

CNS/CS/EE 184 abc. Analog Integrated Circuit Projects Laboratory. *Units by arrangement.* For course description, see Computation and Neural Systems.

EE 191. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering will be arranged. Primarily for undergraduates; students should consult with their advisers. Graded pass/fail.

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.

EE/ChE 270. Special Topics in Systems and Control. *9 units (3-0-6). Prerequisite: E/ChE 102 and consent of instructor.* Topics dependent on class interests and instructor. Instructors: Staff.

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 1 ab. Microcomputers in Engineering. *3 units (0-3-0); E 1 a offered first and second terms; E 1 b offered third term.* A problem-oriented introduction to the microcomputer, its operating system, and computer programming using BASIC. Problems drawn from several engineering disciplines will demonstrate elementary numerical analysis, algorithms, and graphics. In E 1 b other programming languages such as FORTRAN will be introduced in addition to more advanced methods and applications. Students will be expected to complete projects based on the examples provided. Graded pass/fail. Not offered 1990–91.

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.

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 blackboard, overhead projector, and slide projector. Instructors: McDonough, staff.

E 101. Introduction to Automatic Control. *9 units (3-0-6); third term. Prerequisite: EE 32, ChE 105, or equivalent.* Feedback control design, stability, and performance analysis in frequency and time domain. Loop shaping for performance and robustness. Examples from aeronautics, electronics, and chemical engineering. Instructors: Staff.

E/ChE 102 abc. Systems Analysis and Control. *9 units (3-0-6); first, second, third terms. Prerequisites: E 101 or equivalent.* Analysis of linear multivariable systems using state space, frequency domain, and stochastic techniques. Unified treatment using operator theory. Extension of classical control design techniques to multivariable systems. Robustness and (structured) singular value analysis of linear and nonlinear systems. Sampled-data control theory. Design examples from electrical, chemical, mechanical, and aerospace systems. Instructors: Doyle, Morari, Sideris.

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)*

ENGINEERING SCIENCE

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, AM 113 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 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: Wu.

ES 250 abc. Research in Engineering Science. By arrangement with members of the staff, properly qualified graduate students are directed in research in Engineering Science. Hours and units by arrangement.

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, second terms.* 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.* Instructors: Staff.

ENVIRONMENTAL ENGINEERING SCIENCE

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. Registration limited to freshmen and sophomores or with the permission of the instructor.* 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: Hoffmann.

Env 90. Undergraduate 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 encouraged. 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: AMa 95 abc or AM 113 abc (may be taken concurrently); 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. Instructor: Brooks.

Env 116. Experimental Methods in Air Pollution. *9 units (1-4-4); third term. Prerequisite: ChE/Env 157, 158, 159 (may be taken concurrently) or permission of instructor.* Methods of sampling and measurement of particulate and gaseous pollutants. Projects illustrative of problems in aerosol size distribution measurements, instrument calibration, particle characterization, and sampling systems are performed. Instructor: Flagan.

Env 142 ab. Chemistry of Natural Water Systems. *9 units (3-0-6); first, second terms. Prerequisite: Ch 1 abc, Ch 14, or equivalent.* Chemistry of electrolyte solutions, heterogeneous processes, and redox reactions applied to quantitative description of natural waters. Chemical characteristics of lakes, streams, and seawater; comparison of real systems with models; adsorption phenomena; properties of colloids in natural water systems. Instructor: Morgan.

Env 143. Water Chemistry Laboratory. *9 units; third term. Prerequisite: Env 142 ab.* Laboratory experiments and measurements dealing with the major and minor constituents of natural waters. Topics include seawater chemistry, heterogeneous equilibria, rates of precipitation, redox processes, adsorption, and particle coagulation. Measurement techniques include electrometry, spectrophotometry, liquid and gas chromatography, light scattering, and atomic absorption spectrophotometry. Instructors: Hoffmann, Morgan.

Env 144. Ecology. *6 units (2-1-3); first term.* Basic principles of ecology and ways in which human activities can influence natural populations. (May be taught in conjunction with parts of Env 145 a.) Instructor: North.

Env 145 ab. Environmental Biology. *10 units (2-4-4); first term; 9 units (3-0-6); second term.* An exposition of basic biological principles concerning interrelations between organisms, particularly those directly affecting humans and their environment. Extensive reading is required, covering a broad scope of biological literature. Instructor: North.

Env 146. Chemical Reaction Engineering for Water Quality Control. *9 units (3-0-6); first term. Prerequisite: Env 142 a or equivalent (may be taken simultaneously).* 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. Given in alternate years; offered 1991–92. Instructor: Hoffmann.

Env 147. Biochemical Reaction Engineering for Water Quality Control. *9 units. (3-0-6); second term. Prerequisite: Env 146 or permission of instructor.* Fundamental principles of biochemical engineering as applied to wastewater treatment. Design concepts emphasized. Topics: elementary microbiology, fundamentals of microbial metabolism, substrate utilization and kinetics of microbial growth, mixed culture interactions, design and analysis of biological reactors, activated sludge process design, trickling filter design, nitrification, denitrification, anaerobic digestion, microbiology of the sulfur cycle, microbiology of metals. Given in alternate years; offered 1991–92. Instructor: Hoffmann.

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: List.

ChE/Env 157. Combustion and Air Pollution Sources. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Env 158. Air Pollution Aerosols. *9 units (3-0-6).* 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. Given in alternate years; offered 1991–92. Instructor: Lidstrom.

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: Lidstrom.

Env 170. Design of Strategies for Environmental Control. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Principles which underlie the design of efficient and effective solutions to large-scale regional environmental control problems. Environmental data set analysis, mathematical modeling, model verification, and optimization of emission control strategies. Instructor: Cass.

Env/Ch/Ge 175 ab. Environmental Chemistry. *9 units (3-0-6); first, second terms. Prerequisites: Env 142 a or Ch 14; ChE/Env 159 or Ch 135; or permission of the instructor.* A detailed analysis of important chemical reactions and reaction networks in the atmosphere, biosphere, geosphere, and hydrosphere. Fundamental aspects of thermodynamics, kinetics, and mechanisms will be stressed. Given in alternate years; offered 1990–91. 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 206. Special Problems in Biological Engineering Science. *Units by arrangement, any term. Prerequisite: AMa 95 abc.* Special topics in the application of engineering principles to biological and medical problems can be explored on mutual agreement between advanced students and one or more of the participating faculty. Instructor: Wu.

Env 208. Special Topics in Microbiology. *6 units (2-0-4); second term; alternate years. Prerequisite: 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: genetics in unusual microorganisms; risk assessment and the release of genetically engineered organisms to the environment; environmental molecular biology. Given in alternate years; offered 1990–91. Instructor: Lidstrom.

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. Instructor: Lidstrom.

Env 214 abc. Advanced Environmental Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: CE/ME 101 or Ae/APh 101, AMa 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. Not offered 1990–91. Instructor: List.

Env 242 abc. Applied Chemical Kinetics. *9 units (3-0-6); first, second, third terms. Prerequisite: Env 142 ab or permission of instructor.* Fundamental concepts of chemical kinetics as applied to problems in aquatic chemistry, atmospheric chemistry, geochemistry, and water and wastewater treatment. Topics include basic principles, enzyme kinetics, experimental methods, kinetic theories, extrathermodynamic relationships, gas phase kinetics, heterogeneous kinetics, mechanisms, mathematical techniques, microbial kinetics, multiphase systems, oscillating chemical reactions, and solution phase kinetics. Not offered 1990–91. Instructor: Hoffmann.

Env 250. Advanced Environmental Seminar. *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. Introductory Geology. *9 units (3-3-3); first, third terms.* Broad, up-to-date view of the earth, focusing on geological items of current interest: paleomagnetism, mid-oceanic rises, sea-floor spreading, plate tectonics, continental drift, evolution of continental plates, the earth's interior, and environmental geology. Topics vary with the individual instructor and class interests. Classes are limited in size and individually handled by full-time faculty members. All students must be prepared to devote six weekend days to field trips. Instructors: Wyllie, Stolper.

Ge 4. Introduction to the Solar System. *6 units (3-0-3); third term.* An introductory survey of the bodies in our solar system. Meteoritic data and astrophysical observations on young stars provide information on the processes and materials of the early solar system. Interplanetary dust, asteroids, and comets are discussed in relation to the known types of meteorites. The post-Apollo view of the Moon is used as a basis for comparison with other small planets such as the Jovian satellites. Venus and Mars are considered in the light of recent planetary missions; Jupiter and Saturn as examples of outer planets. Offered 1990–91. Instructor: Burnett.

Ge 5. Geobiology. *9 units (3-0-6); second term. Prerequisites: consult instructor.* Biologically related processes and environments in the crust throughout the span of earth history. The environmental influence that the change from a reducing to an oxidizing atmosphere had upon the evolution of life processes and the subsequent progression of organisms and organic activity throughout the oxidizing era. Organic progression and differentiation in time and space in terms of environment. Given in alternate years; offered 1991–92. Instructor: Kirschvink.

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 100. 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. Geology. *9 units (3-3-3); first term. Prerequisites: Ch 1 or 2, Ma 1, Ph 1.* The constitution of the solid earth and the history of its development based on the record preserved in the rocks and observation of ongoing processes. Igneous, sedimentary, and metamorphic processes and products. Geochemistry and geochronology. Evolution of land masses and oceans and their biota through geologic time. Deformation of the earth in plate tectonics; orogenesis. Surface processes and land forms. Glaciation and climatic history. Current state of research. Field trips. Instructor: Silver.

Ge 102. Geophysics. *9 units (2-1-6); second term. Prerequisites: Ma 2, Ph 2.* An introduction to the physics of the earth. The present internal structure of the earth, theories of the origin and evolution of the earth, the earth's gravity and magnetic field, and fundamentals of wave propagation in earth materials. The contributions that heat flow, gravity, paleomagnetic, and earthquake mechanism data have made to our understanding of geodynamics. Instructors: Staff.

Ge 103. Planetary Science. *9 units (3-0-6); first term. Prerequisites: Ma 2, Ph 2.* The planets: their probable composition, physical state, and dynamical behavior. Ground-based observations, spectroscopy, photometry, radio interferometry, radar mapping, observations from spacecraft. Theories of atmospheric structure, surface processes, internal history. Speculations on the origin and evolution of bodies in the solar system. Instructor: Ingersoll.

Ge 104. Geochemistry. *9 units (3-0-6); third term. Prerequisites: Ma 2, Ph 2.* An introduction to geochemical and cosmochemical principles and techniques. Origin of the elements and their classification; origin of the planets. Partitioning of major and trace elements in the earth; geochemical cycles. Applications of thermodynamics and kinetics to geochemistry. Isotope geochemistry of stable and radiogenic nuclides; geothermometry; and geochronology. Instructor: Blake.

Ge 105. The Geologic Record. *9 units (3-3-3); first term.* Introduction to historical geology, including basic principles of biostratigraphy, physical stratigraphy, magnetostratigraphy, geochronology, and tectonics, focused on the interpretation and understanding of biological, geochemical, and tectonic processes and events which have influenced earth history, with particular emphasis on the evolution of the biosphere. One or two weekend field trips to fossiliferous strata and paleoenvironments in the southern California region. Instructor: Kirschvink.

Ge 106. Structural Geology and Tectonics. *9 units (3-3-3); second term. Prerequisite: Ge 101.* Interpretation of the record of deformation of the earth's crust from rock structures on the megascopic (faults, folds), mesoscopic (foliation, lineation), and microscopic (crystal fabric, dislocations) scales. Mechanics of rock deformation. Structural analysis by geometrical and graphical techniques. Structure of major tectonic features of the earth's crust; tectonics of mountain building and sea-floor spreading. Field trips for study of structural features. Instructor: Saleeby.

Ge 107. Geologic Field Mapping. *9 units (0-9-0); third term. Prerequisites: Ge 101, Ge 106.* Introduction to the rationale and techniques of geologic field mapping. Emphasis on construction of a geologic map in a terrain of moderately deformed, stratified rocks. Synthesis and interpretation of field data in the laboratory, including the construction of cross-sections and stratigraphic columns. Two- or three-day field trips. Instructor: Kamb.

Ge 108. Applications of Physics to the Earth Sciences. *9 units (3-0-6); third 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: Muhleman.

Ge 109. Oral Presentation. *2 units (1-0-1); 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. Instructors: Murray, staff.

Ge 110. Sedimentary Geology. *9 units (3-3-3); second term. Prerequisite: Ge 101.* Origin and evolution of sedimentary rocks. 1) Sedimentary materials, processes, and environments; 2) description and classification of sedimentary rocks; 3) interpretation of paleoenvironments and stratigraphic history from field and subsurface observations. Instructors: Murray, staff.

Ge 113. Heterogeneous Phase Equilibrium in Mineral Systems. *9 units (3-0-6); third term.* Principles of phase relationships in mineral-liquid-vapor systems through a range of pressures and temperatures. Unary, binary, ternary, and quaternary systems with examples drawn from systems with components such as silicates, carbonates, salts, H_2O, and CO_2. Given in alternate years; offered 1991–92. Instructor: Wyllie.

Ge 114. Mineralogy. *12 units (3-6-3) or 9 units (3-4-2); first term. Prerequisite: Ge 101.* 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 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.

115 a. Igneous Petrology and Petrography. *12 units (3-6-3) or 6 units (3-0-3) with consent of instructor; second term. Prerequisites: Ge 114, Ch 21 a.* 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: Albee.

115 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 light of chemical equilibrium and experimental studies. Detailed consideration of structure, phase relations, composition, and determination of the major metamorphic minerals. Instructor: Stolper.

Ge 121 abc. Advanced Field and Structural Geology. *12 units (0-9-3); first, second, third terms. Prerequisites: Ge 101, 106, and 107, 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 problems. Instructors: Silver, Sieh, Saleeby.

Ge 123. Summer Field Geology. *15 units (3 weeks, including transportation). Prerequisites: Ge 101, 106, and 107, or consent of instructor.* Advanced field studies in a topical problem during summer break in a remote area of western North America. May be taken in lieu of one quarter of Ge 121 for geology majors, or may be taken in addition to the Ge 121 sequence and applied to requirements for divisional elective units. To be arranged. Instructor: Saleeby.

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 1992–93. Instructor: Kirschvink.

124 a. *9 units (3-3-3); second term. Prerequisites: Ge 101, Ge 105 ab.* The principles of rock magnetism and physical stratigraphy; emphasis on the detailed application of paleomagnetic techniques to determination of the history of the geomagnetic field.

124 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 126. Introduction to Quaternary Geology. *12 units (3-3-6); first term.* An introduction to study of the evolution of the earth's surface during the past million years. Sedimentary, erosional, and tectonic processes involved in the development of landscapes; Pleistocene and Holocene stratigraphy; the use of soils, weathering rates, radiocarbon dating, palynology, and other tools in deciphering recent geological history. The laboratory will involve the use of aerial photographs and an individual research project. Given in alternate years; offered 1990–91. Instructor: Sieh.

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. Given in alternate years; offered 1990–91. Instructor: Burnett.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); first 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 which attempt to describe the chemical state and history of cosmological objects in general and the early solar system in particular. Offered 1990–91. Instructor: Blake.

Ge 131. Origin of the Solar System. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* A critical assessment of the physical processes responsible for the formation of the sun and planets, including astrophysical constraints, gravitational instabilities and accretion discs, formation and early evolution of the giant planets and their satellite systems, terrestrial planetary accretion, primary differentiation, outgassing, and thermal evolution of solid bodies. Given in alternate years; offered 1990–91. Instructor: Stevenson.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Fundamental aspects of atomic and molecular spectra that enable one to infer physical conditions in astronomical, planetary, and terrestrial environments. Topics will include the structure and spectra of atoms, molecules, and solids; transition probabilities; photoionization and recombination; collisional processes; gas-phase chemical reactions; and isotopic fractionation. Each topic will be illustrated with applications in astronomy and planetary sciences, ranging from planetary atmospheres and dense interstellar clouds to the early universe. Given in alternate years; offered 1991–92. Instructor: Blake.

Ge 135. Regional Geology of Southern California (Seminar). *6 units (3-0-3); second term. Prerequisites: Ge 101, Ge 105 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 Southwestern United States. *9 units (1-0-8); third term. Prerequisites: Ge 101 or Ge 105, or instructor's permission.* Includes at least nine days of weekend field trips into areas of 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. Instructors: Staff.

Ge 140 ab. Introduction to Isotope Geochemistry. *6 units (2-0-4); 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.

140 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.

140 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 150. The Nature and Evolution of the Earth. *Units to be arranged. Offered by announcement only.* Discussions at an advanced level of problems of current interest in the earth sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructors: Staff.

Ge 151. Planetary Surfaces. *9 units (3-0-6); third term.* Review of processes responsible for formation and modification of the surfaces of the terrestrial planets, icy satellites, and small bodies, and surface histories so recorded. Topics: exogenic surface processes, especially those associated with 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. Techniques of studying planetary surfaces are also covered in laboratory exercises and lectures. Instructors: Murray, Muhleman.

Ge 152 abc. Atmospheres and Oceans. *9 units (3-0-6); first, second, third terms.* Physical and chemical processes in atmospheric fluid envelopes. First term: atmospheric radiative transfer and remote sensing, atmospheric temperatures and radiative equilibrium, weather and climate. Second term: atmospheric chemistry, numerical modeling, planetary atmospheres. Third term: dynamics of large-scale motions in atmospheres and oceans, physical and chemical oceanography. Instructors: Yung (first and second terms), Ingersoll (third term).

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. Given in alternate years; offered 1991–92. Instructor: Muhleman.

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: Anderson.

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 composition and thermal state of the mantle and core. Instructor: Anderson.

Ge 167. Planetary Physics. *9 units (3-0-6); second term. Prerequisites: Ph 106 abc, AMa 95 abc, or AM 113 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. Offered 1990–91. Instructor: Staff.

Env/Ch/Ge 175 ab. Environmental Chemistry. *9 units (3-0-6).* For course description, see Environmental Engineering Science.

Ge 176. Physics of Earthquakes. *9 units (3-0-6); first term. Prerequisites: AMa 95 abc or instructor's permission.* Study of earth structure and earthquake phenomena by application of physical principles. Emphasis on understanding complex earthquake phenomena in the light of fundamental physical and mathematical concepts. Topics: structure of the earth in relation to propagation of earthquake waves, static and dynamic models of earthquakes, interpretation of far- and near-field phenomena, significance of earthquakes in plate tectonics, and problems pertaining to earthquake prediction. Instructor: Kanamori.

Ge 177. Geology of Earthquakes. *9 units (3-0-6); second term. Prerequisites: Ge 104, 105, and 106 or equivalents.* 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; offered 1991–92. Instructor: Sieh.

Ge 203. Advanced Atmospheres and Oceans. *9 units (3-0-6); third term. Prerequisite: Ge 152 or equivalent.* Advanced topics pertaining to the dynamics, thermodynamics, and chemistry of atmospheres and oceans. Theory of radiative transfer in planetary atmospheres. Offered 1990–91. Instructor: Yung.

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. Given in alternate years; offered in 1990–91. Instructor: Taylor.

Ge 213. Advanced Seminar in the Earth and Planetary Sciences. *Units and prerequisites dependent upon topics. Offered by announcement only.* Seminar on special topics and problems of current interest.

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 1990–91. 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.*

215 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. Given in alternate years; offered 1991–92. Instructor: Taylor.

215 b. Advanced Igneous Petrology. *Second term.* Lectures, seminars, and laboratory studies on igneous petrogenesis and rocks, emphasizing experimental studies. Given in alternate years; offered 1991–92. Instructor: Stolper.

215 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. Given in alternate years; offered 1991–92. Instructor: Albee.

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 226. Observational Planetary Astronomy. *9 units (3-3-3); second term.* Optical and infrared radiation detectors, spectrometers, polarimeters, and photometers will be discussed in the context of the observational study of the planets. Other topics will include the design of observational programs and the assessment of the reliability of data by critical analysis of observational literature. Observing experience will be required at the telescope. Given in alternate years; offered 1990–91. Instructors: Staff.

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. Given in alternate years; offered 1991–92. Instructor: Kamb.

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. Given in alternate years; offered 1991–92. Instructor: Burnett.

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. Offered 1991–92. Instructor: Wasserburg.

Ge 242. Metal Pathways Through Terrestrial and Marine Ecosystems. *6 units (2-0-4); third term. Prerequisite: instructor's approval.* Sources of lead and some other trace metals in the atmosphere, their depositions on oceans and land plants, their cycling through ecosystems, modes of their introduction to and removal from the oceans, and anthropogenic perturbations of their natural cycles. Instructor: Patterson.

Ge 244 ab. Paleoecology Seminar. *5 units; second, third terms.* Critical review of classic investigations and current research in paleoecology and biogeochemistry. Instructor: Kirschvink.

Ge 247. Tectonics of the North American Cordillera. *9 units (3-0-6); first term. Prerequisite: Ge 121 abc or instructor's approval.* Major structural features of the North American Cordillera, and the present physical state of the crust and upper mantle; craton-ocean plate interactions; analysis of displaced crustal fragments; reactivation of cratonic crust; regional stratigraphic patterns; tectonic significance of igneous and metamorphic belts; relation of neotectonic patterns to paleotectonic records. Given every three years; offered 1991–92. Instructor: Saleeby.

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. Given in alternate years; not offered 1990–91.

Ge 260. Mineral Physics. *9 units (3-2-4); third term. Offered by announcement only. 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, and high-pressure electrical properties of minerals and application of shock and ultrasonic equation-of-state data to earth and planetary interiors. Instructor: Ahrens.

Ge 261 abc. Advanced Seismology. *9 units (3-0-6); first, second, third terms. Prerequisite: AMa 95 or equivalent.* Essential material in modern seismology; elastic wave propagation, ray theory, normal mode theory, free oscillations, applications to determination of earth structure and earthquake source mechanism, interpretation of seismograms, geophysical time series analysis and synthesis. Instructors: Harkrider, Helmberger.

Ge 265. Geophysical 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, convolutional models, deconvolution, autoregressive-moving average models, spectral analysis, missing data, model fitting, and two-dimensional and multichannel analysis. Instructor: Clayton.

Ge 266. Analysis of Seismic Reflection Data. *9 units (3-0-6); third term. Prerequisites: partial differential equations and/or permission of instructor.* The analysis of densely recorded reflection data as it relates to exploration geophysics. Topics: review of acoustic wave theory, layered earth models, one-way extrapolations operators, migration methods, velocity estimation, multiple suppression, statics, slant stacks, and inversion methods. Instructor: Clayton.

Ge 268. Inverse Problems in Geophysics. *9 units (3-0-6); second term. Prerequisite: Linear algebra or permission of instructor.* Basic concepts in inverse theory: singular value decomposition, generalized inverse, resolving kernels, and error estimation. Application to selected geophysical problems such as 1D and 3D seismic velocity and attenuation structures in the earth from body and surface waves, density structure from gravity, and normal modes. Instructor: Tanimoto.

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. Participation in a one-week field excursion during spring break may be required. Instructors: Sieh, staff.

Ge 282 abc. Geological Sciences Seminar. *1 unit; first, second, third terms.* Presentation of papers by invited investigators. In charge: Tanimoto, 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)*

HISTORY

These courses are open only to students who have fulfilled the freshman humanities requirement.

H 40. Reading in History. *Units to be determined for the individual by the department. 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 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.

H 110. Early Modern Europe.* *9 units (3-0-6); first term.* Topics in social and economic history of Europe up to the 19th century, with special attention to quantitative analysis. Topics will include the crisis of the later Middle Ages, violence and religious change, and revolution and political stability. Instructor: Hoffman.

H 111 ab. The Italian City-State.* *9 units (3-0-6); two terms; each can be taken separately.* H 111 a: the general political phenomenon of the city-state, and the reactions of Italian thinkers, such as Dante and Machiavelli, to the problems of such societies. H 111 b: will usually concentrate on Venice, unique among the city-states. Instructor: Searle.

H 112. Contemporary Europe.* *9 units (3-0-6).* Public issues, social trends, and cultural developments of special interest in Europe today. Instructors: Staff.

H 113. The Great War 1914–1945.* *9 units (3-0-6).* How and why "The Great War" (as World War I was once called) began, was fought, recessed in 1919, resumed in 1939 (we called this World War II), and ended at last, leaving Europe cruelly transformed, deeply divided, and condemned as it turned out to further conflict of a different sort—the Cold War. Focus on politics and war and the major movements and figures of the period. The Russian Revolution, fascism, the Spanish Civil War, the German occupation of Europe, Lenin, Mussolini, Hitler, Stalin, Churchill, de Gaulle. Instructor: Fay.

H 114. European Intellectual History.* *9 units (3-0-6).* Topics in the history of European thought since the Enlightenment. Emphasis on philosophy and social theory, and their relations to political, economic, and social developments. Instructors: Staff.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

H 115. Science, Weapons, and National Security.* *9 units (2-0-7).* The history of the arms race since 1945, with particular attention to its domestic sources, including defense R & D, the scientific community, the national security bureaucracy, Congress, and the president. Instructor: Kevles.

H 118. Britain and Her Empire.* *9 units (3-0-6).* Books, both nonfiction and fiction, that illuminate such subjects and persons in British history after 1815 as the army, the aristocracy, industrial advance and decline, imperial expansion and contraction, the working man, Queen Victoria, Winston Churchill, and George Orwell. Instructor: Fay.

H 122. British India.* *9 units (3-0-6).* Indian politics and society since the Sepoy Rebellion (1857), with particular attention to Gandhi and the winning of independence (1947). Reading will include Gandhi's *Autobiography* and at least one novel. Instructor: Fay.

H 124. Population and Family History.* *9 units (3-0-6).* 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.

H/Hum 131. History on Film.* *9 units (2-2-5).* 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 132. Japan.* *9 units (3-0-6); third term.* An introduction to Japanese civilization, past and present. The interrelation between art, culture, philosophy, politics, and society. 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. Instructor: Lee.

H 134. History of Late Imperial China, 1200–1800.* *9 units (3-0-6).* 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.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

H 135. History of Modern China, 1800–present.* *9 units (3-0-6).* Main events of 19th- and 20th-century China, with various interpretations of their historical significance. Focus: modern roots of the Chinese revolution beginning with Sun Yat-Sen. Instructor: Lee.

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 146. American Biography.* *9 units (3-0-6).* Leading Americans as seen through the best of their biographies, with an examination of the changing methods in the art of biography. Instructor: Ridge.

H 147. The Far West and the Great Plains.* *9 units (3-0-6).* The exploration and development of the great regions of western America. Special attention will be paid to the influence of the natural environment, and the exploitation of it by such industries as the fur trade, mining, cattle ranching, farming, and oil. Instructor: Ridge.

H 148. The Supreme Court in U.S. History.* *9 units (3-0-6).* The development of the Supreme Court, its doctrines, and its role in U.S. history through analyses of selected cases. Instructor: Kousser.

H 149. American Radicalism.* *9 units (3-0-6); second term.* The nature of dissident American social and political movements in the 19th and 20th centuries; emphasis on their critiques of American life, role in society, and contributions. Instructor: Rosenstone.

H 150. Problems in the History of English Law and Society.* *9 units (3-0-6).* Aspects of the development of law and society in pre-industrial England. Topics will include the relationship between actions at common law, legal administration, legislation, social structure, and the economic basis of society. Instructor: Searle.

H 151. The Shaping of Modern America, 1890–1917.* *9 units (3-0-6).* Selected social, economic, and political trends of the era, such as immigration, urbanization, and reform. Instructor: Kousser.

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.

H 153 ab. America Since World War II.* *9 units (3-0-6); second, third terms.* Topics in the recent social, cultural, and political history of the United States. First term is not a prerequisite for second term. Instructor: Kevles.

H 154. American Social History.* *9 units (3-0-6).* The evolution of American society since 1800, with particular emphasis on class, gender, race, and ethnicity. Instructor: Flamming.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement.* *See page 105.*

H 155. The American Worker.* *9 units (3-0-6).* Examines the development of the American working class in the 19th and 20th centuries, with emphasis on radicalism, class consciousness, working-class culture, and unionization. Instructor: Flamming.

H 156. The History of Modern Science.* *9 units (3-0-6).* Selected topics in the development of the physical and biological sciences since the 17th century, with emphasis on the evolution of scientific ideas as a problem in intellectual history. Instructors: D. Barkan, Kevles.

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.

H 158. The Scientific Revolution.* *9 units (3-0-6).* 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: D. Barkan.

H 159. Science and Society.* *9 units (3-0-6).* A historical examination from a socioeconomic, political, and ethical perspective of selected issues in science and technology—for example, biotechnology, human reproduction, nuclear power, the environment. Instructor: Kevles.

H 160 ab. History of the Modern Physical Sciences.* *9 units (3-0-6).* 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 developments 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.) Instructor: D. Barkan.

H 161. Selected Topics in History. *9 units (3-0-6). Advanced credit to be determined on a course-by-course basis by instructor.* Instructors: Staff and visiting lecturers.

H 201. Reading and Research for Graduate Students. *Units to be determined for the individual by the staff.*

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

HUMANITIES

All courses numbered 1 through 20 are freshman humanities courses. Courses numbered above 20 are open only to students who have fulfilled the freshman humanities requirements.

Hum 1 ab. Greek Civilization. *9 units (3-0-6); first and second or second and third terms.* Introduction to Greek culture from Homer to Aristotle. Hum 1 a is a prerequisite for Hum 1 b. Instructors: philosophy and literature staff.

Hum 2 ab. Traditional Europe: Society, Material Life, and Values before 1800. *9 units (3-0-6); first and second terms.* Introduction to patterns of life and thought in pre-industrial Europe, stressing the structure of economic, political, and cultural life. First quarter: 300 A.D.–1400 A.D.; second quarter: 1300–1800. Instructors: history staff.

Hum 3 ab. Early European Literature. *9 units (3-0-6); first and second or second and third terms.* Critical exploration of selected literature, chiefly English, from the Middle Ages, the Renaissance, or the Restoration. Depending on the instructor, continental authors such as Dante, Rabelais, or Molière may also be covered. Instructors: literature staff.

Hum 6 ab. The Modern Age. *9 units (3-0-6); first and second or second and third terms.* Since the middle of the 19th century, historical, economic, and cultural pressures have redefined Western society. Using a variety of artistic, literary, philosophical, and historical works, this two-quarter sequence will introduce students to aspects of the history, politics, thought, literature, art, and culture of modernity. Instructors: literature and history staff.

Hum 7 ab. American Society and Politics. *9 units (3-0-6); first and second or second and third terms.* An introduction to the major events and forces that shaped the American past, and the way historians and biographers have analyzed them. Depending on the instructor, topics covered may include: the Revolution and the Constitution, the Civil War and Reconstruction, the New Deal, immigration, industrialization, technological change, and 20th-century political movements and culture. Instructors: history staff.

Hum 8 ab. American Literature and Culture. *9 units (3-0-6); first and second and second and third terms.* Studies in American ideas, styles, and general culture from the colonial period to the present. Emphasis on those characteristic features of American experience that have influenced and continue to affect our culture and character. Students may take two quarters of either element or one quarter of each. Instructors: literature and history staff.

Hum 9 ab. Introduction to Asia. *9 units (3-0-6); first and second and second and third terms.* Asia, which may be taken to stretch from Beirut to Beijing and beyond, contains a variety of peoples whose only common property is that they have been defined in opposition to what is "European." This two-term sequence will attempt to introduce students to the history, culture, and present state of *some* of these. The choice, varying from year to year, will generally be made from East Asia, South Asia, or the Middle East. Instructors: history and literature staff.

Hum 10 ab. Morality, Society, and Politics. *9 units (3-0-6); first and second or second and third terms.* Theories of morality and politics have generally been shaped not only by the broader intellectual climate of their time, but also by the perceived virtues and defects of the social and political conditions of the time. This two-quarter sequence will provide an introduction to the moral and political theories which helped shape Western societies, with the emphasis on the seventeenth century to the present. The first quarter will concentrate on moral theory and the second quarter on political theory. Each theory will be presented in historical context but will also be assessed for its relevance to contemporary life and politics. Instructors: philosophy staff.

Hum 12 ab. Belief, Truth, and Knowledge. *9 units (3-0-6).* Introduction to philosophical theories regarding the nature of knowledge and the justification of belief. Particular topics covered may include: skepticism, the nature of science and scientific knowledge, logic, the relationship between language and the world, and the nature of moral and aesthetic judgments. Readings will include both historical and contemporary philosophical texts. Instructors: philosophy staff.

Hum 13. Autobiography and the Arts of Self-Expression. *9 units (3-0-6); first or second or third term.* Introduction to the genre of European and American autobiography. Among authors who may be studied are: St. Augustine, Benjamin Franklin, Rousseau, Anthony Trollope, Frederick Douglass, Henry Adams, Mary McCarthy, Maxine Hong Kingston, and Maya Angelou. The course aims to explore these authors' techniques of self-construction in their writing. There is emphasis in the course on the student's own writing skills and instruction in advanced composition (see page 105). Instructor: Staff.

Hum 104. Plato.* *9 units (3-0-6).* The course will read the major dialogues. Studies the Socratic Myth *(Protagoras, Euthyphro, Apology, Crito)*, the Platonic Eros *(Phaedrus, Symposium)*, and the *Republic* and selections from the *Laws*. Class reports and final paper. Instructors: Staff.

Hum 119. Selected Topics in Humanities. *9 units (3-0-6).* Advanced courses to be determined on a course-by-course basis by the instructor. Instructors: Staff and visitors.

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).* 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 pre-film lectures and post-film discussions, to do some reading, and to produce a short paper. Instructor: Rosenstone.

Hum 133. Topics in Film History.* *9 units (2-2-5).* 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.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

Hum 140 ab. The History of the Book.* *9 units (3-0-6).* 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. Instructor: Sutherland.

Hum 141 a. Offensive Literature.* *9 units (3-0-6).* A survey of literature deemed at various historical periods to be seditious, blasphemous, obscene, or libelous. Instructor: Sutherland.

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 131 for complete details.

JAPANESE *(See Languages)*

JET PROPULSION

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.* Modern aspects of rocket, turbine, electrical, and nuclear propulsion systems and the principles of their application to lifting, ballistic, and space flight 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, inlets and diffusers. Nuclear rockets, nuclear air breathing cycles. Instructor: Zukoski.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

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. Instructors: Staff.

JP 213. Dynamics of Reacting Gases. *9 units (3-0-6); each term. Prerequisites: Ae/APh 101 abc or CE/ME 101 abc, or equivalent.* Application of gas dynamic and chemical principles to 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: Zukoski.

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 and visiting lecturers.

L 102 abc. Elementary French. *10 units (3-1-6); first, second, third terms.* The course aims at providing reading knowledge plus competence in general conversation. Students who have had French in secondary school or college must consult with the instructor before registering. Not open to students with more than one previous year of French. Instructors: Staff.

L 103 abc. Intermediate French. *9 units (3-0-6); first, second, third terms. Prerequisite: L 102 abc or equivalent.* Grammar review, conversation practice, introduction to French history, literature, and politics. Literary readings and writing are emphasized in the second and third quarters. Instructors: Staff.

L 105. French Literature. *9 units (3-0-6). Prerequisite: L 103 abc or equivalent. Advanced humanities credit will be determined by the instructor.* A body of French literature is treated from the standpoint of a dominant theme. Conducted in French. Instructors: Staff.

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. Instructors: Staff.

L 107 abc. Intermediate Japanese. *10 units (3-1-6); first, second, third 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. Instructors: Staff.

L 108 abc. Technical Japanese. *10 units (3-1-6); first, second, third terms. Prerequisite: L 107 or equivalent. (Not available for Humanities and Social Sciences credit.)* Primarily reading and translation of technical texts in the natural and applied sciences. Recognition of the 1850 "general-use characters," as well as more specialized technical vocabulary. Instructors: Staff.

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. Instructors: Staff.

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. Instructors: Staff.

L 140 abc. German Literature. *9 units (3-0-6); first, second, third terms. Prerequisite: L 132 abc or equivalent. Advanced Humanities credit to be determined by the instructor.* The reading and discussion of works by selected 19th- and 20th-century authors. Conducted in German. Instructors: Staff.

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. Instructor: Lindholm.

L/Lit 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6). Advanced Humanities credit to be determined by the instructor.* First term: French "classical" literature of the 17th and 18th centuries; second term: from 1939 to the present, and with literary responses to "the Absurd." Readings are in English, but students may read French originals. Instructor: A. Smith.

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. Instructors: Staff.

L/Lit 154. French Literature in Translation: The French Novel. *9 units (3-0-6); first term. Advanced Humanities credit to be determined by the instructor.* Famous novels of the 16th to the 20th century are read against their historical, sociological, and philosophical background. Readings and discussions are in English, but students may read the French originals. Instructor: A. Smith.

L/Lit 160 ab. German Literature in Translation.* *9 units (3-0-6).* First term: Middle Ages through the Classic/Romantic Age. Second term: 19th and 20th centuries, and exile literature. Instructors: 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 Soviet 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. Advanced Humanities credit to be determined by 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.

L/Lit 167 abc. Latin Literature.* *9 units (3-0-6); first, second, third terms. Prerequisite: three years of high school Latin or equivalent.* Major Latin authors, usually one per term. Instructor: Pigman.

LATIN *(See Languages)*

LINGUISTICS

Lin 101 a. Introductory Linguistics. *9 units (3-0-6).* Language is a system that carries meaning to sound. Phonology is the study of sound; semantics is the study of meaning. Syntax is about the ways we go from phonology to semantics. Phonetics, phonemic theory, morphology, phrase structure grammar, transformational grammar. Extensive reading required. Instructor: B. Thompson.

Lin 101 b. Linguistic Theory. *9 units (2-1-6).* Current models of language structure, especially in syntax and semantics. Transformational generative grammar, case grammar, generative semantics, semantic theories. A research project is required. Instructor: B. Thompson.

Lin/SS 103. Psycholinguistics. *9 units (2-1-6); third term.* A seminar-type course on language behavior as a reflection of conceptual processes. Language acquisition, aphasia and other language disturbances, linguistic memory and grammar organization, language and the brain, multilingualism. A research project is required. Instructor: B. Thompson.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

Lin/SS 104. Sociolinguistics. *9 units (2-1-6).* Seminar and research on language in social interaction. Experiments required. Readings in language variation (dialects, slang, jargon, scientific, and other). Instructor: B. Thompson.

Lin/SS 105. Computational Linguistics. *9 units (2-1-6); first term. Prerequisite: Lin 101 a or Lin 101 b or equivalent.* English as a language for communication with computers. Problems in parsing and semantic data base analysis. Review through readings of natural language processing systems, including speech recognition and other AI (artificial intelligence) applications. Research required. Instructors: B. Thompson, F. Thompson.

LITERATURE

These courses are open only to students who have fulfilled the freshman humanities requirements.

Lit 30. Reading in English. *Units to be determined for the individual by the department.* 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 department. Graded pass/fail. Instructors: Staff. *Not available for credit toward humanities-social science requirement.*

Lit 31. Summer Reading. *Units to be determined for the individual by the department. Maximum 9 units.* Reading in literature, history, and other fields during summer vacation; books to be selected from a recommended reading list, or in consultation with a member of the staff. Critical essays on reading will be required. Graded pass/fail.

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 100. Introduction to 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 answer these and other basic questions, a substantial range of poems, from simple to complex, will be read and discussed. Instructor: Mandel.

Lit 103 ab. The Epic of Return.* *9 units (3-0-6); second, third terms.* The *Odyssey* and its transformations. First term: the *Odyssey,* the *Aeneid,* Augustine's *Confessions,* and Dante's *Divine Comedy;* second term: *Paradise Lost* and *Ulysses.* The first term is a prerequisite for the second. Instructor: Bush.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement.* *See page 105.*

Lit 108 abc. Seminar in Creative Writing. *9 units (3-0-6).* Students will develop their writing skills chiefly through their own creative efforts. Lecturers will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Specifically, the subject for any quarter may be fiction, autobiography, poetry, the essay, or other forms. Information on each quarter's focus will be provided by the Registrar. Enrollment is limited and upperclass undergraduates will be given priority. Students may apply one quarter of Lit 108 to the 36-unit H&SS requirement. Instructors: Staff.

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. First term: Skelton, More, Spenser, Marston, Wyatt, Marlowe, Shakespeare (sonnets), Jonson. Second term: Middleton, Webster, Donne, Herbert, Vaughan, Crashaw, Marvell. Instructors: La Belle, Pigman.

Lit 114 ab. Shakespeare.* *9 units (3-0-6). 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 (3-0-6).* Milton's important short works, his epics, and selections from his prose will be read against the background of the major issues of the 17th century. Instructor: Pigman.

Lit 122 abc. The English Novel.* *9 units (3-0-6); third term.* Development of the English novel from the 18th century to the present. First term: early novelists, through Scott; second term: the great Victorians; third term: modern British and Irish novelists. Instructor: Sutherland.

Lit 130 abc. The 19th- and 20th-Century Novel.* *9 units (3-0-6).* A three-term exploration of the late 19th- and 20th-century European, British, and American novel. No term is a prerequisite to the other terms. A study of the great seminal figures. Instructor: D. Smith.

Lit 131. Vision and Community in American Literature.* *9 units (3-0-6).* An examination of one of the central tensions in the American experience, from its beginnings in the Anne Hutchinson trial to its manifestation in the work of T. S. Eliot. Instructor: Bush.

Lit 132. American Naissance-Renaissance.* *9 units (3-0-6).* 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.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

Lit 138. The Gilded Age.* *9 units (3-0-6).* 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. Instructor: Weinstein.

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 *Finnegans Wake.* Instructor: Bush.

Lit 146 ab. 20th-Century American and British Poetry.* *9 units (3-0-6); second, third terms.* A two-term seminar on the major poets and poetic theories from the turn of the century to the present. First term: American poets; second term (may be taken independently of the first): British poets. Instructor: Bush.

Lit/Psy 150. Psychoanalysis and Literature.* *9 units (3-0-6); first, second terms.* The application of concepts from contemporary psychoanalytic theory to literature, including such ideas as the unconscious, interpretation, the relation of childhood experience to adult personality, and the nature and function of dreams. Authors covered will vary from term to term and may include Dostoevsky, Kafka, Thomas Mann, and selected 20th-century novelists. Instructor: Breger. *May be taken to satisfy advanced humanities requirement or option elective requirement in social science.*

L/Lit 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6).* For course description, see Languages.

L/Lit 154. French Literature in Translation: The French Novel. *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 165 abc. Russian Literature in Translation.* *9 units (3-0-6).* For course description, see Languages.

L/Lit 167 abc. Latin Literature.* *9 units (3-0-6).* For course description, see Languages.

Lit 170 abc. From Mysteries to Absurdism: A Survey of Drama. *9 units (3-0-6).* First term: origins of "modern" drama, from the Middle Ages to the Classical Age in 17th-century France. Second term: theater from the "Age of Elegance" in the late 17th century to the "Triumph of the Bourgeoisie" in the 19th century. Third term: theater from Ibsen to the present. Not offered on a pass/fail basis. Instructor: Mandel.

Lit 180. Special Topics in Literature. *9 units (3-0-6). See Registrar's announcement for details.* Advanced credit to be determined on a course-by-course basis by the instructor. Instructors: Staff.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

MATERIALS SCIENCE

MS 15 abc. Principles of Materials. *9 units; (3-0-6) first, second term; (1-4-4) third term.* The principles involved in the selection, the thermal treatment, and the mechanical treatment of engineering materials. Metallic materials, with some consideration given to ceramics and polymers. Emphasis on the utilization of phase transformations and strengthening mechanisms to obtain desired properties. Instructors: Fultz (MS 15 a), Freise (MS 15 b), Christman (MS 15 c).

MS 90. Materials Science Laboratory. *9 units (1-6-2); third term. Prerequisite: MS 15 or equivalent or may be taken concurrently.* An introductory laboratory in relationships between structure and properties of crystalline solids. Experiments involve structure determination by x-ray diffraction, mechanical property measurements, and crystal defect observation by chemical etching, x-ray topography, and transmission electron microscopy. Individual projects may be performed, depending upon the student's interests and abilities. Instructor: Vreeland.

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. Mechanical Behavior of Metals. *9 units (3-0-6); second term. Prerequisites: AM 97 abc, MS 5 abc.* Mechanical behavior of metals for engineering applications. Elastic behavior of anisotropic materials and polycrystalline aggregates. Yielding, plastic flow, and strengthening mechanisms; influence of temperature and rate of loading on plastic deformation. Fracture of metals by ductile flow, brittle cracking, fatigue, and creep. Behavior under impact loading. Not offered 1990–91. Instructor: Christman.

MS 120. Kinetics of Crystal Imperfections. *9 units (3-0-6); first term.* Treatment of crystal imperfections, their interactions, and their influence on some physical and mechanical properties; taught at the level of Friedel, *Dislocations.* Instructor: Christman.

MS 121. Phase Transformations in Solids. *9 units (3-0-6); third term. Prerequisites: APh/ME 17 abc and MS 15 a, or graduate standing.* Diffusion from atomistic and continuum viewpoints. Thermodynamics and kinetics of first- and second-order phase transformations, decomposition, and ordering reactions. Role of strain energy in solid-solid phase transformations. Diffusionless transformations. Microstructural morphologies. Instructor: Fultz.

APh/MS 122. Diffraction Theory and Applications. *9 units (3-0-6).* For course description, see Applied Physics.

MS 123. Transmission Electron Microscopy Laboratory. *9 units (0-7-2); third term. Prerequisite: APh/MS 122.* Techniques of using the transmission electron microscope (TEM) for the characterization of materials. Operation and alignment of the TEM. Bright field, dark field, and diffraction techniques with specimen tilting. Specimen preparation. Experiments include studies of crystal defects and solid-state precipitation reactions by diffraction contrast methods, and an introduction to high-resolution TEM. Instructor: Ahn.

MS 131. Crystal Defects. *9 units (1-6-2); second term. Prerequisite: MS 120.* Techniques used in the study of crystal defects and their influence on physical and mechanical properties; relationship between crystal structure and properties studied in experiments that utilize optical microscopy, electron microscopy, and x-ray topography. Instructor: Vreeland.

APh/MS 140. Ion Beam Modification and Analysis of Materials. *6 units (2-0-4).* For course description, see Applied Physics.

APh/MS 141 abc. Ion Beam Analysis Laboratory. *5 units (0-4-1).* For course description, see Applied Physics.

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 ab. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aeronautics.

MS 300. Thesis Research.

MATHEMATICS

Ma 1 abc. Freshman Mathematics. *9 units (4-0-5); first, second, third terms. Prerequisites: high school algebra and trigonometry.* Calculus, ordinary differential equations, and infinite series. Linear algebra, vectors, and analytic geometry. Instructor: Fuller.

Ma 1 bc, 2a. Freshman Mathematics, Advanced Placement. *9 units (4-0-5); first, second, third terms.* Instructor: Apostol.

Ma 2 abc. Sophomore Mathematics. *9 units (4-0-5); first, second, third terms.* A continuation of the topics introduced in Ma 1, including linear algebra, calculus of several variables, and probability. Instructors: Luxemburg, Ramakrishnan.

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. Not offered 1990–91.

Ma 5 abc. Introduction to Abstract Algebra. *9 units (3-0-6); first, second, third terms.* Groups, rings, fields, and vector spaces are presented as axiomatic systems. The structure of these systems is studied, making use of the techniques of automorphisms, homomorphisms, linear transformations, subsystems, direct products, and representation theory. Many examples are treated in detail. Instructor: Wales.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 1 abc.* Set theory, the Peano axiom system and elementary number theory, graph theory, paths and trees, generating functions. Algebraic structures, semigroups, permutation groups, automata, lattices, and Boolean algebras. Finite fields and coding theory. Linear programming. Mathematical logic, propositional calculus and predicate calculus, models, and Godel's completeness and incompleteness theorem. Natural deduction. Instructor: Montenegro.

The courses labeled Ma 91 or Ma 191 are one-shot courses reflecting the interests of faculty, visitors, and students. The list below is a selection of titles of Ma 91, Ma 191, and regular courses that have been offered in recent years: Harmonic Analysis in the Complex Plane, Several Complex Variables, Entire Functions and the Fourier Transform, Almost Periodic Functions, Elementary Theory of Meromorphic Functions, Banach Algebras, Asymptotic Series, Theory of von Neumann Algebras, Functional Equations, Uniformly Distributed Sequences Modulo 1, Operational Calculus, Algebraic Geometry, Diophantine Analysis, Representation Theory, Introduction to Lie Algebras, Geometry and Mechanics of Space Curves, Differential Topology, Fixed Point Theory, Coding Theory, Introduction to the Constructive Theory of Functions, Multiparticle Scattering Theory.

Ma 91. Knot Theory for Beginners. *9 units (3-0-6); second term.* Instructor: Gabai.

Other Ma 91 titles may be announced.

Ma 92 abc. Senior Thesis. *9 units (0-0-9); first, second, third terms. Prerequisite: approval of adviser.* Open only to seniors who are qualified to pursue independent reading and research. The work must begin in the first or second term and be supervised by a member of the staff. Students will submit a thesis at the end of the year. Graded pass/fail.

Ma 98. Reading. *3 units or more by arrangement.* Occasionally a supervised reading course will be offered. Topics, hours, and units by arrangement. Only qualified students will be admitted after consultation with the instructor in charge of the course. Graded pass/fail.

Ma 102 a. Differential Geometry of Curves and Surfaces. *9 units (3-0-6); third term. Prerequisite: Ma 108 ab or permission of instructor.* An introduction to the geometry of smooth curves and surfaces in three dimensions. Frenet formulae, first and second fundamental forms, curvature of surfaces, Gauss-Bonnet theorem. Not offered 1990–91.

Ma 104. Introduction to Complex Variables. *9 units (3-0-6); second term. Prerequisite: Ma 2 ab.* Topology of plane regions, Cauchy-Riemann equations, Cauchy integral formula, series expansions, analytic continuation, Laurent expansions, and residue calculus. Instructor: Ulmer.

Ma 107. Introduction to Analysis. *9 units (4-0-5); first term. Prerequisite: Ma 2 a and Ma 2 b or equivalent.* Elementary set theory. Topology of metric spaces, compactness, connectedness, convergence, completeness, continuity. Calculus of several variables. Contraction mappings, existence and uniqueness of solutions of ordinary differential equations, implicit function theorem. Instructor: Collins.

Ma 108 ab. Classical Analysis. *9 units (3-0-6); second, third terms. Prerequisite: Ma 107 or equivalent. May be taken concurrently with Ma 109 ab.* Lebesgue integral. Fourier analysis. Analytic functions of one complex variable, including classification of isolated singularities and analytic continuation. Instructor: Collins.

Ma 109 ab. Geometric Analysis. *9 units (3-0-6); second, third terms. Prerequisite: Ma 107 or equivalent. May be taken concurrently with Ma 108 ab.* Differential manifolds, differential forms, and orientability. Fundamental group and universal covering space. Degree of map. Riemannian metric, geodesics, curvature, Gauss-Bonnet formula. Elements of calculus of variations, Euler-Lagrange equation. Instructor: Lewis.

Ma 110 abc. Real and Complex Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 108 a or equivalent.* First term: Theory of analytic functions, contour integration, conformal mappings. Additional material as time allows. Second and third terms: Measure theory and Lebesgue integration, Fubini's theorem, the Radon-Nikodym theorem and the Riesz representation theorem. General topology, Banach spaces, duality, Lebesgue L^P-spaces, Hilbert spaces. Applications to the theory of Fourier series and integrals. Instructor: Seco.

Ma 112 a. Statistics. *9 units (3-0-6); first term only.* The first term is an introductory course in the basic techniques of probability theory, hypothesis testing, and regression analysis. The second and third terms include analysis of variance, estimation, nonparametric inference, sequential analysis, decision theory, and exploratory data analysis. Instructor: Lorden.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 abc or equivalent.* First order logic and model theory; computability theory, undecidability, and Gödel's incompleteness theorems; set theory, the axiom of choice, and the continuum hypothesis. Instructor: Kechris.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 abc or equivalent.* 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. Given in alternate years; not offered 1990–91. Instructors: Kastanas, Kechris.

Ma 120 abc. Abstract Algebra. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 abc or equivalent.* Abstract development of the basic structure theorems of groups, commutative and noncommutative rings, lattices, and fields. Instructor: Aschbacher.

Ma 121 abc. Combinatorial Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5.* Elementary and advanced theory of permutations and combinations. Theory of partitions. Theorems on choice including Ramsey's theorem and the Hall-König theorem. Existence and construction of block designs with reference to statistical design of experiments, linear programming, and finite geometries. Instructor: Wilson.

Ma 122 abc. Topics in Group Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 abc or consent of instructor.* Representations of finite groups and compact Lie groups. Semisimple Lie algebras—classification and representations. Introduction to commutative algebra via affine group schemes. Rigid tensor categories and tannakian categories. Quasi-tannakian categories, quantum groups, knot invariants. Instructor: Anderson.

EE/Ma 126. Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ma 127 ab. 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).* For course description, see Computer Science.

Ma 142 abc. Introduction to Partial Differential Equations. *9 units (3-0-6); first, second, third terms. Prerequisite for Ma 142 a: Ma 108. Ma 109 a is desirable. Prerequisite for Ma 142 bc: Ma 142 a and Ma 110 bc concurrently.* Ma 142 a (ordinary differential equations): existence theory, linear systems and stability, global properties of flows on surfaces, Sturm-Liouville theory of second order linear equations, method of characteristics for quasilinear first order partial differential equations. Ma 142 bc: Laplace equation, heat equation, wave equation, general existence and uniqueness questions, the Cauchy-Kowalevski theorem, Sobolev spaces, and elliptic regularity. Further topics at the discretion of the instructor. Instructor: Wolff.

Ma 144 a. Probability. *9 units (3-0-6); first term.* Basic theory, including characteristic functions and limit theorems, random walk, Markov chains, Poisson process, Brownian motion. Instructor: Lewis.

Ma 145 abc. Introduction to Unitary Group Representations. *9 units (3-0-6); first, second, third terms.* Not offered 1990–91.

Ma 147 abc. Introduction to Dynamical Systems and Ergodic Theory. *9 units (3-0-6).* Not offered 1990–91.

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, Hamenstadt.

Ma 160 ab. Number Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ma 108 ab or equivalent.* Topics selected from: elementary number theory, zeta functions, distribution of primes, modular functions, asymptotic theory of partitions, geometry of numbers, ideal theory in algebraic number fields, units, valuations, discriminants, differents, and local theory. Instructor: Ulmer.

Ma 191 a. Algebraic Geometry. *9 units (3-0-6); first term.* Instructor: Ramakrishnan.

Ma 191 b. Algebraic Geometry. *9 units (3-0-6); second term.* Instructor: Laumon.

Ma 191 c. Algebraic Geometry. *9 units (3-0-6); third term.* Instructor: Ramakrishnan.

Ma 191 d. Knot Theory for Beginners. *9 units (3-0-6); second term.* Instructor: Gabai.

Ma 191 e. Topics in Low Dimensional Topology. *9 units (3-0-6); second term.* Instructor: Gabai.

Ma 191 f. Theory of Positive Operators. *9 units (3-0-6); second term.* Instructor: Luxemburg.

Ma 191 g. Topics in Mathematical Physics. *9 units (3-0-6); second, third terms.* Instructor: Graf.

Other Ma 191 titles may be announced.

Ma 216 a. Advanced Mathematical Logic. *9 units (3-0-6); third term. Prerequisite: Ma 116 or equivalent.* Topics to be chosen from model theory and its applications to algebra, infinitary logic and admissible sets, ordinary and generalized recursion theory, consistency and independence results in set theory, large cardinals, descriptive set theory. Content varies from year to year so that students may take the course in successive years. Instructor: Jech.

Ma 218 a. Advanced Complex Analysis. *9 units (3-0-6); second term. Prerequisite: Ma 110 abc or permission of instructor.* Topics of current research interest in one-variable complex analysis and potential theory. Instructor: Makarov.

Ma 290. Reading. *Hours and units by arrangement.* Occasionally, advanced work is given by a reading course under the direction of an instructor.

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. *9 units. Three terms.* Instructor: Kechris.

Ma 324 abc. Seminar in Combinatorics. Instructor: Wilson.

Ma 325 abc. Seminar in Algebra. *6 units. Three terms.* Instructors: Aschbacher, Wales.

Ma 345 abc. Seminar in Analysis. *6 units. Three terms.* Instructor: Luxemburg.

Ma 390. Research. *Units by arrangement.*

Ma 392. Research Conference. *Three terms.*

See also the list of courses in Applied Mathematics.

MECHANICAL ENGINEERING

APh/ME 17 abc. Thermodynamics. *9 units (3-0-6).* For course description, see Applied Physics.

ME 19 abc. Fluid Mechanics and Gasdynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 abc, 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 22 abc. Introduction to Thermal Engineering. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 ab, ME 19 ab.* The principles of thermal energy transfer and thermal power conversion. Analyses of open and closed cycles with and without phase change, emphasizing applications to power conversion systems. Basic principles of fluid dynamic machines. Combustion, flame temperature, thermochemistry. Heat transfer by conduction, convection, heat exchangers, radiative transfer, solar energy, cooling towers. Instructors: Hunt, Acosta.

ME 71. Introduction to Design. *9 units (3-3-3); second term.* Introduction to visualization and fabrication techniques used in engineering design. Basic aspects of projective geometry, graphical techniques, and computer-aided design needed for spatial visualization, communication, and creative design. Introduction to engineering design 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 simple working models. Instructors: Staff.

ME 72. Engineering Design Laboratory. *12 units (3-9-0); first term. Prerequisites: AM 35 abc, ME 71, or permission of instructor.* 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 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 Physics Division. Instructor: Antonsson.

ME 73 ab. Machine Component Design. *9 units (3-4-2); second, third terms. 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. Offered alternate years. Not offered 1990–91. Instructor: Antonsson.

ME 96. Mechanical Engineering Laboratory. *9 units; offered third term only. Prerequisites: upper division standing, permission of instructor.* A laboratory course emphasizing measurement methods, data acquisition and analysis, with special reference to experiments in thermal fluid science and mechanical systems. Instructor: Burdick.

ME 100. Advanced Work in Mechanical Engineering. The staff in mechanical engineering will arrange special courses on 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.

CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

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 staff to meet the needs of individual students as appropriate. Instructors: Staff.

ME 115. Introduction to Kinematics. *9 units (3-0-6); first term. Prerequisite: basic linear algebra.* Introduction to the study of planar, rotational, and spatial motions with applications to mechanism analysis, robotics, and mechanics. Topics in kinematic analysis will include screw theory, rotational representations (such as quaternions), matrix groups, dual number theory, Lie algebras, and Clifford algebras. Applications include mobility in mechanisms, kinematics of closed and open chain mechanisms, and robots. Instructor: Burdick.

ME 118 abc. Advanced Heat Transfer. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 19, ME 22, AMa 95 or equivalent, CE/ME 101 or Ae 101 (may be taken concurrently).* First two quarters cover conservation equations for momentum, energy and mass transfer, conduction heat transfer in solids, phase change processes, convective heat and mass transfer in laminar and turbulent flows, buoyancy driven flows, and some special applications. Third quarter is directed to topics in thermal radiation, including blackbody radiation, radiative properties of materials, radiation exchange between surfaces, the equation of transfer for participating media, gas radiation, and scattering by small particles. Instructors: Hunt, Acosta, Goodwin.

ME 120 ab. Thermal Physics. *9 units (3-0-6); first, second terms. Prerequisites: APh 17 abc, ME 19 ab, or equivalents.* Introduction to the microscopic physical phenomena underlying macroscopic fluid behavior. The first term will cover the kinetic theory of gases, chemical thermodynamics, statistical mechanics, and transport processes. The second term will focus on inelastic radiative and collisional processes, and an introduction to partially ionized gases. Selected applications to combustion, plasmas, and high-speed flows will be discussed. Instructor: Goodwin.

Ae/ME 130. Introduction to Control of Mechanical Systems. *9 units (3-0-6).* For course description, see Aeronautics.

ME 135 ab. Vehicle Design for Mars Surface Exploration. *9 units (2-0-7); second and third terms. No prerequisites. Open only to seniors and graduate students.* Seminar and project course covering wheeled and legged locomotion and navigation with applications to vehicle design for Mars and other interplanetary exploration. Topics include multi-legged quasi-static gait analysis, dynamically stable running, and navigation in uneven terrain. Not offered 1990–91. Instructors: Burdick, Culick.

ME 141 ab. Modeling the Dynamics of Physical Systems. *9 units (3-0-6); first and second terms. Prerequisites: AMa 95 abc or AMa 113 abc (may be taken concurrently), AM 35 abc, E 1 or CS 10, or equivalent.* Virtually all engineering systems exhibit a dynamic exchange of energy, often between regimes (e.g., electrical to mechanical in a motor). Modeling of these dynamic interactions, and generation of the governing differential equations of state can be accomplished readily using the technique of Bond Graph modeling, particularly useful for non-linear systems, systems with multiple forms of energy transmission and storage, and transducer systems including oscillation, amplifiers, feedback, and control. They provide a single comprehensive framework for the study of dynamic system behavior. Discussion to include energy transfer, power pairs, duality, causality, and physical analogs. Not offered 1990–91. Instructors: Staff.

ME 171 ab. Computer-Aided Engineering Design. *9 units (3-0-6); second, third terms. Prerequisites: AMa 95 abc or AMa 113 abc, AM 35 abc, ME 72 abc, E 1 or CS 10, or equivalent. Knowledge of PASCAL, C, or FORTRAN.* 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 multi-variable optimization; optimal design; and symbolic manipulation. Assessment of CAD as an aid to the design process. Students will design several parts and/or a complete device. Offered alternate years. Instructor: Antonsson.

ME 200. Advanced Work in Mechanical Engineering. The staff in mechanical engineering will arrange special courses on problems to meet the needs of advanced graduate students.

ME 201 abc. Turbomachines. *6 units (2-0-4); first, second, third terms. Prerequisite: CE/ME 101 or instructor's permission.* The theory and operation of hydraulic fluid machines, principally pumps, and turbines. Recent two- and three-dimensional inviscid flow design theories. Special consideration to the effects of cavitation in methods of design and behavior of large systems. Not offered every year. Instructor: Acosta.

ME 202 abc. Engineering Two-Phase Flows. *9 units (3-0-6). Prerequisites: AMa 95 abc, 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 1990–91. Instructor: Brennen.

ME 230. Advanced Robotics. *9 units (3-0-6); third term. Prerequisites: ME 115 or equivalent.* This course focuses on current topics in robotics research. Past topics have included advanced manipulator kinematics, grasping and dextrous manipulation with multifingered hands, obstacle avoidance and motion planning algorithms, and multilegged walking machines. The lectures will be divided between a review of appropriate analytical techniques and a survey of current research literature. Course work will include an independent research/development project chosen by the student. Not offered 1990–91. Instructor: Burdick.

ME 300. Thesis Research.

Many 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.

MUSIC

Mu 21. Elements of Music. *9 units (3-0-6); first term.* The Listening Experience I: How to listen and what to listen for in classical and other musical expressions. Theoretical concepts taught for comprehension rather than complete mastery of skills. No previous musical experience necessary. Course is focused for the non-musician and is a strongly recommended prerequisite for all other music courses. Instructor: Britton.

Mu 22. Form in Music. *9 units (3-0-6); second term. Recommended prerequisite: Mu 21.* The Listening Experience II: Guided listening, analysis, and discussion of various "musical architectures" or forms, theme and variation, sonata form, symphonic form, keyboard, chamber, and choral genres. Instructor: Britton.

Mu 23. Style in Music. *9 units (3-0-6); third term. Recommended prerequisites: Mu 21 and Mu 22.* The Listening Experience III: Guided listening, analysis, and discussion of compositional elements and techniques used in different musical epochs. An historical overview of musical styles from the Middle Ages to the 20th century. Instructor: Britton.

Mu 27. Fundamentals of Music Theory and Elementary Ear Training. *9 units (3-0-6); first term. 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: Britton.

Mu 28. Harmony I. *9 units (3-0-6); second term. Prerequisite: Mu 27 or entrance exam.* Study of tonal harmony and intermediate music theory; techniques of chord progression, modulation, and melody writing according to common practice; ear training continued. Instructor: Britton.

Mu 29. Harmony II. *9 units (3-0-6); third term. Prerequisite: Mu 28 or entrance exam.* More advanced concepts of music theory, including chromatic harmony, and 20th-century procedures relating to selected popular music styles; ear training continued. Instructor: Britton.

Mu 30. Special Topics in Western Music History. *9 units (3-0-6); first term; however, term offered may vary due to possibility of coordination with significant off-campus events.* A consideration of selected composers and/or subjects, e.g., the symphonic form, in greater depth than normally possible in the general survey courses. Specific course content to be announced prior to preregistration. Given in alternate years; not offered in 1990–91. Instructor: Britton.

Mu 31. Medieval and Renaissance Music History. *9 units (3-0-6); first term, alternate years.* Development of Western music from the ancient Greeks through medieval monasteries and cathedrals to the chapels, courts, and countryside of the high Renaissance. Includes listening and discussion of style of representative music. Instructor: Britton.

Mu 32. Music History of the Baroque Era. *9 units (3-0-6); second term, alternate years.* Survey of the musical forms and composers active between 1600 and 1750; spans the development of opera, cantata, oratorio, keyboard, chamber, and orchestral music through the mature masterworks of Bach and Handel. Instructor: Britton.

Mu 33. Music of the Age of Enlightenment. *9 units (3-0-6); third term, alternate years.* Music of the so-called "pre-Classic" and "Classic" periods (ca. 1750–1825), with emphasis on C. P. E. Bach, Haydn, Mozart, and the early works of Beethoven. Instructor: Britton.

Mu 34. Music History of the Early Romantics. *9 units (3-0-6); first term, alternate years.* Examines concepts of Romanticism found in other ages, and a wealth of music from late Beethoven, Schubert, Mendelssohn, Schumann, Chopin, and others to Franz Liszt. Instructor: Britton.

Mu 35. Music History of the Late Romantics. *9 units (3-0-6); second term, alternate years.* Explores the music of the late-19th-century Nationalists as well as the forward-looking works of Liszt, Wagner, Mahler, Strauss, and others. Instructor: Britton.

Mu 36. The New Music: Music History of the 20th Century. *9 units (3-0-6); third term, alternate years.* The diversity of musical styles found in the 20th century. Impressionistic, tonal, atonal, aleatoric, electronic and other avant-garde compositions, and their philosophical-sociological implications. Instructor: Britton.

Mu 50. Introduction to the Music of Asia. *9 units (3-0-6); first term.* This course will survey the music and related performance traditions of South, Southeast, and East Asia. Each musical tradition will be discussed, using the techniques of ethnomusicology, history, anthropology, and organology (the study of musical instruments). The cultural significance of musical performances in court, village, tribal, urban, and religious contexts will be explored, based on readings and class lectures. These will be illustrated by recordings, live demonstrations by Asian musicians, and videotapes and films of actual performances. For final reports, students will be encouraged to attend local Asian events involving music. A music background is not required. Instructor: Staff.

Mu 51. Music of East Asia. *9 units (3-0-6); third term.* This course will explore the music and related performance traditions found in China, Mongolia, Japan, and Korea. Ancient sources on music in China will be discussed, followed by a study of the forms of Chinese opera, chamber music, and modern developments during and after the Cultural Revolution. A wide variety of traditional Japanese forms such as Noh, Kabuki, Bunraku, Gagaku, and Sankyoku will lead to a study of contemporary Japanese art music involving indigenous and Western instruments, as well as modern popular forms such as Shigin, and the uses of music in Japanese Buddhist ritual. Readings from Chinese and Japanese literature will enhance the discussions of social and cultural patterns governing musical performance. Tibetan Buddhist ritual music and dance, opera, and folk forms will be explored. No music background required. Instructor: Staff.

Mu 52. Music of Southeast Asia. *9 units (3-0-6).* This course will explore the musical traditions of mainland and insular Southeast Asia: Burma, Thailand, Laos, Cambodia, Vietnam, the hill tribes of the Southeast mainland, Malaysia, the Philippines, and Oceania. The various gong-chime ensembles (such as the gamelan) will be compared and contrasted from musical and cultural points of view. The uses of music in conjunction with language will be explored through examples from syncretic theatrical forms involving poetry, puppetry, and dance. The relationship of tonal languages to music will be discussed. The construction of musical instruments, particularly gong-making, will be a focus of the course. No music background required. Instructor: Staff.

Mu 53. Music and Dances of India. *9 units (3-0-6); second term.* Survey of music and dances of India, with live performances, films, and tapes. Also instruction in playing the sitar. Instructors: Staff.

Mu 101. Selected Topics in Music. *Units to be determined by arrangement with instructor.* Instructors: Staff and visiting lecturers.

EE/Mu 107 abc. Projects in Music and Science. *Units to be individually arranged, up to a maximum of 9.* For course description, see Electrical Engineering.

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. Journalism. *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. Choral Music. *3 units (0-3-0); first, second, third terms.* Instruction in choral ensembles, such as men's and women's glee clubs. Instructors: Staff.

PA 31 abc. Chamber Music. *3 units (0-3-0); first, second, third terms.* Instruction in performing chamber music. Instructors: Staff.

PA 32 abc. Orchestral Music. *3 units (0-3-0); first, second, third terms.* Instruction related to participation in a symphony orchestra. Instructors: Staff.

PA 33 abc. Instrumental Music. *3 units (0-3-0); first, second, third terms.* Instruction related to the performance of instrumental music either as solo instrument or in group performance. Currently offered in three sections: wind ensemble, jazz band, and guitar class. Instructors: Staff.

PA 40 abc. Theater Arts. *3 units (2-0-1); first, second, third terms.* Instruction related to the production of dramatic presentations, including plays, musicals, dramatic readings, etc. Instructors: Staff.

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 60 abc. Studio Arts. *3 units (0-3-0); first, second, third terms.* Instruction in "hands-on" art—currently sculpture and painting/drawing. Instructors: Staff.

PHILOSOPHY

These courses are open only to students who have fulfilled the freshman humanities requirements.

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 85. Philosophy and Current Issues.* *9 units (2-0-7).* Selected current issues involving conflicts about moral right and wrong will be studied, and the various sources of those conflicts investigated. The issues studied will vary but will include some of the following: medical experimentation and the allocation of medical resources; the alleged "right to life," and its bearing upon abortion, capital punishment, and euthanasia; political liberty and the prohibition of certain minority activities under criminal sanctions (e.g., the use and sale of designated drugs, morally offensive publications, prostitution); civil disobedience and conscientious objection; majority and minority rights. If the course is oversubscribed, preference will be given to students who have successfully completed Hum 10 ab. Instructors: Staff.

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6).* Instructors: Staff and visiting lecturers.

Pl 122. Philosophy of Science.* *9 units (3-0-6); first term.* An introduction to fundamental philosophical problems concerning the nature of science. Topics: the character of scientific explanation, criteria for the confirmation and falsification of scientific theories, the relationship between theory and observation, the objectivity of science, and issues having to do with the ways in which scientific knowledge changes over time. Not offered 1990–91. Instructor: Woodward.

Pl 125. Philosophy and Biology.* *9 units (3-0-6).* Philosophical and conceptual issues relating to the biological sciences. Topics covered may include: the logical structure of evolutionary theory, units of selection, optimization theory, the nature of species, reductionism, teleological and functional reasoning, and ethical issues arising from contemporary biological research. Instructor: Hilbert.

Pl 131. Philosophy of Mind and Psychology.* *9 units (3-0-6).* Philosophical issues regarding the nature of mind and the impact of recent developments in cognitive science on these issues. Topics may include: the nature of belief and other psychological attitudes, perception, mental imagery, and behavior, all with a focus on relevant empirical work. Instructors: Hilbert, Woodward.

Ec/Pl 147. Altruism and Fairness in Economics.* *9 units (3-0-6).* For course description, see Economics.

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

Pl 150. History of Early Modern Philosophy. *9 units (3-0-6).* 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. Not offered 1990–91. Instructors: Donagan, Hilbert.

Pl 181. Democracy.* *9 units (3-0-6).* Alternative concepts of democracy and alternative justifications of a democratic political system, particularly the role of participation and representation in democratic theory. Relevant empirical materials will be presented. Instructor: Staff.

Pl 182. Ethics and International Relations.* *9 units (3-0-6).* The course considers whether moral criteria can or should apply to the conduct of international affairs. The topics treated, which will vary with the instructor, include: war and morality; the special problems of nuclear war; disarmament; economic distribution; migration. Instructors: Staff.

Pl 190. Political Philosophy and Public Policy.* *9 units (2-0-7); third term.* A critical examination of methods used in the systematic analysis of public policy alternatives, such as cost-benefit and risk-benefit analysis. Not offered 1990–91. Instructors: Staff.

PHYSICAL COMPUTATION AND COMPLEX SYSTEMS *(See Physics)*

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

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, electricity and magnetism, and special relativity. Emphasis on physical insight, problem solving, and practical electricity. Graded pass/fail. Lecturers: Goodstein, McKeown, Pine. Section leaders: Barnes, Kimble, Newman, Phillips, Rempe, Whaling, Zmuidzinas, and others.

Ph 2 abc. Waves, Quantum Mechanics, and Statistical Physics.* *9 units (4-0-5); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, or their equivalents.* The second year of a two-year introductory course in classical and modern physics. Topics to be covered include classical waves, introductory quantum mechanics, thermodynamics, and statistical mechanics. Lecturers: Gomez, Politzer, Barnes. Section leaders: Raab, Gomez, and others.

Ph 3. Physics Laboratory. *6 units; first, second, third terms.* 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 systems, and radioactivity. The content of each term is identical and only one term may be taken for credit. Graded pass/fail. Instructors: Gomez, Skelton.

Ph 4. Physics Laboratory. *6 units; third term only. Prerequisite: Ph 3 or equivalent.* One laboratory period per week, plus other activities outside the lab. Choice of a variety of experiments encompassing both classical and atomic physics. Examples: the transient response of a resonant circuit, the Millikan oil drop experiment, electron diffraction, viscosity, diffraction of electromagnetic waves, and sound waves in a cavity. Graded pass/fail. Instructors: Gomez, Skelton.

Ph 5. Physics Laboratory. *9 units; first term. Prerequisites: Ph 1 abc, Ph 2 a or Ph 12 a (or taken concurrently), and Ph 3 or equivalent.* Continuation of Ph 3. Measurements of physical quantities, their analysis, and assignment of errors are stressed. Most of the experiments are concerned with topics in the theoretical courses Ph 2 a or Ph 12 a, but experiments in electrostatics and direct currents are also included. Instructors: Gomez, Skelton.

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: Gomez, Skelton.

**Students may transfer from Ph 12 to Ph 2 any time during the quarter, but before the last day for dropping courses. The final grade will be based on the combined record in the two courses.*

Ph 7. Physics Laboratory. *9 units; third term. Prerequisite: Ph 5 or 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: Gomez, Skelton.

Ph 10 abc. Frontiers in Physics. *3 units (2-0-1); first, second, third 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: Tombrello.

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 from Ph 10 a will be offered the opportunity to enroll in this tutorial, the purpose of which is to demonstrate how research ideas arise, 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. Quantum and Statistical Mechanics.* *9 units (3-0-6); 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: 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: McKeown, Porter, Preskill.

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. Instructors: Barish, Soifer.

20. *3 units (0-3-0); first, second terms. Prerequisite: CCO 1 or equivalent experience with computers.* Introduction to computing and its application to problems in classical mechanics. Use of spreadsheets in physical problems, numerical integration, and numerical simulation of differential equations of motion. Simulation of orbital mechanics.

21. *3 units (0-3-0); second, third terms. Prerequisite: Ph 20 or equivalent experience with computers and numerical techniques.* Introduction to the use of symbolic manipulation programs and expert systems for mathematics. Use of root-finding and Monte Carlo numerical techniques. Multi-variable minimization techniques including neural networks. Discrete-element electromagnetism.

22. *3 units (0-3-0); third term. Prerequisite: Ph 20 or Ph 21 or equivalent experience with computers.* Laboratory applications of computers. Interfacing computers to external sensors and control elements. One supervised project involving development of a computer hardware interface.

**Students may transfer from Ph 12 to Ph 2 any time during the quarter, but before the last day for dropping courses. The final grade will be based on the combined record in the two courses.*

Ph 77 ab. Advanced Physics Laboratory. *9 units; first, second, third terms. Prerequisites: Ph 5 or 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: Boehm, Marcley.

Ph 78 abc. Senior Thesis Experimental. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research, open only to senior physics majors. Requirements will be set by individual faculty members, but will include a term paper based upon laboratory experience. Selection of topics and final report must be approved by the Physics Undergraduate Committee. Not offered on pass/fail basis. Instructors: Staff. See note below.

Ph 79 abc. Senior Thesis Theoretical. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research, open only to senior physics majors. Requirements will be set by individual faculty members, but will include a term paper based on the work performed. Selection of topics and final report must be approved by the Physics Undergraduate Committee. Not offered on pass/fail basis. Instructors: Staff.

Note: Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the chairperson of the Physics Undergraduate Committee, or any other member of the committee. A grade will not be assigned in Ph 78 or Ph 79 until the completion of the thesis, which is normally expected to take three terms. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ph 98 abc. Quantum Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 12 abc or, with permission of the instructor, Ph 2 abc, Ma 2 abc, or their equivalents.* A one-year course in quantum mechanics and its applications, for students who have completed Ph 12. Scattering theory, approximation methods, symmetries, spin-½ systems, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructor: Weinstein.

Ph 101 abc. Critical Transitions. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 2 or Ph 12.* How simple, microscopic laws produce phenomena with many relevant scales. Familiar critical transitions (liquid-gas and magnetization) occur as temperature varies, while in quantum systems they can occur as a function of field strength. Tools of statistical mechanics and the renormalization group will be developed to address these and a variety of analogous problems in solid-state, low-temperature, and high-energy physics. Other applications include percolation, polymerization, liquid crystals, and chaotic nonlinear systems. Not offered 1990–91.

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.

Ph 103 a. *First term.* Particle physics without accelerators. Emphasis will be on the neutrino mass, mixing, and charge conjugation properties. The course will stress physical concepts, and both experimental techniques and theoretical methods will be presented. Related topics, such as the relevant problems in astrophysics (solar neutrinos, dark matter, supernovae) and cosmology (critical density, primordial nucleosynthesis) will also be discussed. Possible ways to use similar techniques in searches of other "exotic" particles (axions, majorons, heavy leptons, etc.) will be included if time permits. Instructor: Vogel.

Ph 103 b. *Second term.* Order-of-magnitude physics. 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. The course will provide training for a final exam open to all Caltech students. Prizes totaling $5,000 will be awarded for the best performances on the exam. Instructors: Goldreich, Phinney.

Ph 103 c. *Third term.* Nonlinear dynamics. An introduction to modern dynamics emphasizing applications to natural systems. Topics will include Hamiltonian mechanics, dissipative systems, and the use of maps to simulate both. We will study KAM theory and examples of periodic orbits, resonances, chaos, period doubling, intermittancy, fractals, and strange attractors. Instructors: Goldreich, Malhotra, Murray.

Ph 106 abc. Topics in Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 abc or Ph 12 abc, Ma 2 abc.* An intermediate course in application of basic principles of classical physics to a wide variety of subjects. Roughly half of the year will be devoted to mechanics, and half to electromagnetism. Topics include Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, boundary value problems, multipole expansions, and various applications of electromagnetic theory. Instructors: Preskill, Weichman, Cross, Kavanagh.

Ph 118 abc. Electronic Circuits and Their Application to Physical Research. *9 units (3-0-6); first, second, third terms.* 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. Typically given in alternate years. In 1990–91, offered second and third terms. Instructor: Drever.

Ph 125 abc. Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 2 abc. Recommended: AMa 95 abc or Ma 108 abc. Not available to students who have completed Ph 98 abc.* A fundamental course in quantum mechanics aimed at understanding the mathematical structure of the theory and its application to physical phenomena at the atomic, nuclear, and elementary particle levels. Various formulations of quantum mechanics, properties of operators, one-dimensional and central potentials, angular momentum and spin, scattering theory, perturbation theory, identical particles, and introductory relativistic quantum theory. Instructor: Simon.

Ph 127 abc. Statistical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 98 abc or Ph 125 abc, Ph 106 abc.* A thorough introduction to statistical problems in physics. Topics: fundamental laws and concepts of thermodynamics, kinetic theory and transport phenomena, statistical mechanics, and the connection between macroscopic and atomic laws. Not offered 1990–91.

Ph 129 abc. Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106 abc or the equivalent. Recommended: AMa 95 abc or Ma 108 abc.* Practical methods of summing series, integrating, and solving differential equations, including numerical methods. The special functions (Bessel, Elliptic, Gamma, etc.) arising in physics, as well as partial differential equations, orthogonal functions, integral equations and transforms, tensors, linear spaces and operators, group theory, and probability and statistics. Instructors: Porter, Schwarz.

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 each of three distinct areas. In 1990–91, nuclear physics, elementary particle physics, and quantum optics. Terms may be taken separately. Instructors: Filippone, Telegdi, Kimble.

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: Blandford, Thorne.

Ph 151 ab. Algorithms and Applications of Physical Computation and Complex Systems. *9 units (3-3-3); first, second terms.* Computational techniques and the relation between the physical structure of problems and computers, illustrated by applications in a variety of scientific fields. Cellular automata, parallel algorithms, and multiscale methods will be covered. The course will use parallel computers, including hypercube computers and the Connection Machine. Not offered 1990–91.

Ph 161. Introduction to Complex Systems. *9 units (3-3-3); second term. Prerequisites: Ph 106, Ph 129, Ph 136 or equivalent.* Introduction to complex systems and associated physical optimization methods, including simulated annealing, neural networks, elastic nets, and genetic algorithms. Use of complex systems theory to model performance of parallel computers. Not offered 1990–91.

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 supervision of an instructor. Approval of instructor and of student's departmental adviser or registration representative must be obtained before registering. Graded pass/fail.

Ph 172. Experimental Research in Physics. *Units in accordance with work accomplished.* Approval of student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics and PCCS. *Units in accordance with work accomplished.* Approval of student's research supervisor and departmental adviser or registration representative must be obtained before registering. Graded pass/fail.

Ph 176 ab. Advanced Computational Physics Laboratory. *6 units (0-5-1); second, third terms. Prerequisites: Ph 98, Ph 106, AMa 95 (all may be taken concurrently).* A two-term course in the use of computers to model classical and quantum mechanical systems, with emphasis on numerical techniques and on building intuition for the behavior of these simulations. Students are guided through a series of projects carried out in modern computer environments, e.g., PCs and concurrent processors. Not offered 1990–91.

CNS/Bi/Ph 185. Collective 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 98 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. In 1990–91, offered second term only as a sequel to Ph 135 a. Instructor: Filippone.

Ph 205 abc. Relativistic Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or Ph 98.* 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: Frautschi.

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.

Ph 222 abc. Many-Body Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or Ph 98.* The concepts and formal tools needed to study many-particle systems. Applications to specific physical systems of interest in condensed matter and nuclear physics: electron gas, superconductors, liquid helium, nuclear matter, and finite nuclei. Not offered 1990–91.

Ph/APh 223 abc. Topics in Condensed Matter Physics. *9 units (3-0-6); first, second, and third terms. Prerequisites: Ph 98 or Ph 125 or equivalent, APh 105, or permission of instructor.* Content includes advanced theoretical and experimental topics at the frontier of research in condensed matter physics, and will vary from year to year. In 1990–91, topics will include: electronic and transport properties of materials, superconductivity (including conventional and high-temperature superconductivity), superfluidity, phase transitions and critical phenomena. Instructor: Yeh (offered second and third terms only in 1990–91).

Ph 224 abc. Space Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 98, Ph 106, or equivalent.* Experimental and theoretical aspects of X-ray, cosmic-ray, and gamma-ray astrophysics, with emphasis on topics of current interest. Analysis of astronomical and technical aspects of the four great space observatories of the near future: the Hubble Space Telescope, GRO, AXAF, and SIRTF. Instructors: Prince, Djorgovski, Mould. (Note: Ph 224 c counts as equivalent to Ay 212 for Ay graduate students.)

Ph 228 ab. Topics in Mathematical Physics. *9 units (3-0-6). Prerequisite: instructor's permission.* Content changes from year to year. Not offered 1990–91.

Ph 229 abc. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms.* Content changes from year to year. Only offered third term 1990–91.

Ph 229 c. *Third term.* A course on the renormalization group and lattice QCD. The course will review critical phenomena and Statistical Mechanics. Scaling and Universality will be introduced and explained using the renormalization group. After discussing some simple spin models, nonlinear sigma models will be introduced as prototypes of field theory, followed by the $\lambda\phi^4$ theory. Formulation of lattice QCD and its application to the calculation of the hadron and glueball spectrum, heavy quark potential, bounds on the Higgs mass, and weak interaction matrix elements. Lastly, finite temperature field theory will be discussed. Instructor: Gupta.

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, with emphasis on quantum chromodynamics, quark-gluon theory of strong interactions, including renormalization, confinement, chiral symmetry breaking, anomalies, perturbation theory for high energy, and lattice calculations. Instructor: Zachariasen.

Ph 231 abc. High-Energy Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 98 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. Instructor: Hitlin.

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)xSU(2)xU(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. Offered alternate years. Instructor: Wise.

Ph 235 abc. Introduction to String Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 230 and Ph 236 (both may be taken concurrently).* Classical and quantum theory of relativistic strings, both bosonic and supersymmetric, with emphasis on the problem of unification. Calculation of tree and one-loop amplitudes. Other topics include compactification of extra dimensions, conformal field theory, and heterotic string phenomenology. Offered alternate years; not offered 1990–91.

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 Leighton's* Principles of Modern Physics. A systematic exposition of Einstein's general theory of relativity, with emphasis on applications to astrophysical and cosmological problems. Offered alternate years; not offered 1990–91.

Ph 237 abc. Theoretical Nuclear Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 98 or equivalent.* Microscopic models for finite nuclei. Topics: second quantization, Slater determinants, nuclear shell model, Hartree-Fock model, pairing, collective vibrations and rotations. Not offered 1990–91.

Ph 240 ab. Simplicity and Complexity. *6 units (2-0-4); first, second, third terms.* Only offered first and third terms 1990–91.

Ph 240 a. *First term.* Topics in simplicity and complexity, including measurement and observation in quantum mechanics; quantum cosmology; definitions of complexity; entropy and the physics of information; the second law of thermodynamics and the arrows of time; chaos; and the relation of physics and chemistry to the other sciences. Instructor: Gell-Mann.

Ph 240 b. *Third term.* Attempts to describe some general properties of adaptive complex systems. Ph 240 b will be accessible to students without a background in quantum mechanics or Ph 240 a. Instructor: Gell-Mann.

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. Graded pass/fail. Instructors: Cross, Phillips.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 or Ph 173 when the student has progressed to the point where research leads directly toward the thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

POLITICAL SCIENCE

PS/SS 12. Introduction to Political Science. *9 units (3-0-6); second and third terms.* Introduction to the tools and concepts of analytical political science. Subject matter is primarily American political processes and institutions. Topics: spatial models of voting, redistributive voting, games, presidential campaign strategy, Congress, congressional-bureaucratic relations, and coverage of political issues by the mass media. Instructors: Staff.

PS 101. Selected Topics in Political Science. *Units to be determined by arrangement with the instructor.* Instructors: Staff.

PS 109. The Presidency. *9 units (3-0-6); first term.* Presidential elections, executive branch relations, the role of the president in shaping foreign and domestic policy, and the substantial institutional constraints on the exercise of presidential power. Instructors: Staff.

PS 112. Behavioral Basis of Politics. *9 units (3-0-6).* The development of political attitudes and public opinion. Topics: the role of the mass media, peer groups, and social institutions in the formation and stabilization of political opinions. Instructor: Kiewiet.

PS/SS 116. War, Diplomacy, and International Politics. *9 units (3-0-6). Prerequisite: PS/SS 12 or SS 13.* Various theories of the sources and resolution of international conflicts. The second half will apply these theories to case studies of conflicts such as the First and Second World Wars, the Vietnam War, the Cold War, and the Arab-Israeli conflict. Instructor: Staff.

PS 118. Democratic Theory. *9 units (3-0-6); third term.* This course will raise several types of questions and answer none. Is it possible to have a democracy? How ought citizens to act in a democracy? How do democratic governments and citizens of democratic politics actually behave? Is a democratic government necessarily just? Instructor: Staff.

PS/SS 119. The Politics of the Industrial State. *9 units (3-0-6). Prerequisite: PS/SS 12 or equivalent.* The institutions of and the behavior within industrialized democracies of the western world. Instructors: Kiewiet, Kousser.

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. Instructor: Kiewiet.

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. Instructors: Staff.

PS/SS 122. Noncooperative Games in Social Science. *9 units (3-0-6); first term. Prerequisite: PS/SS 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/SS 123. Cooperation and Social Behavior. *9 units (3-0-6). Prerequisite: PS/SS 122 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: McKelvey.

PS/SS 125. Peasant Politics. *9 units (3-0-6); second term. Prerequisite: PS/SS 12 or SS 13.* The political role of the peasantry, with attention to rural political organization and the effect of market relationships. Instructor: Hoffman.

PS 126. Bureaucratic Politics. *9 units (3-0-6); third term.* Survey and critical analysis of the literature on bureaucratic politics. Topics: bureaucracies as organizations, bureaucracies as part of a larger political environment, and formal models of bureaucratic behavior. Instructors: Staff.

PS 127. Interest Groups in American Politics. *9 units (3-0-6); first term.* Survey of the literature on organized groups. Topics: who joins; internal politics of organizations; activities of interest groups in the larger political arena. An effort will be made to assess interest groups within the context of theories of democracy. Instructors: Staff.

PS 132. Formal Theories in Political Science. *9 units (3-0-6); third term. Prerequisite: PS/ SS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theoretic and social choice models and models of political processes based on them. Instructors: Staff.

Ec/PS 134. The Political Economy of Urban Areas. *9 units (3-0-6).* For course description, see Economics.

PS 135. Political Geography of Developing Countries. *9 units (2-0-7); first term.* A study of the swift transition from colonialism or an undeveloped state to the present that includes the growth of one-party states; the role of the military; tribal, religious, and class pressures; the internal and external role of boundaries; and new foreign policies. Instructors: Staff.

PS/SS 139. Comparative Politics. *9 units (3-0-6); second term. Prerequisite: PS/SS 12 or SS 13.* The politics of non-American political systems. Areas of study: the politics of non-democratic 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. Instructors: Staff.

PSYCHOLOGY

Psy 10. Introduction to Psychological Development. *9 units (3-0-6); first, second terms.* A study of the psychological development of the individual within a context of biological, cultural, and social evolution. Not offered 1990–91. Instructor: Breger.

Psy 12. Introduction to Abnormal Psychology. *9 units (3-0-6); second term.* The development of mental and emotional disturbances. Basic theory will be reviewed in relation to selected case material and relevant research. Instructor: Breger.

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.

Psy 101. Selected Topics in Psychology. *Units to be determined by arrangement with the instructor; third term.* Instructor: Breger.

Psy 110. Psychological Development. *9 units (3-0-6); first, second terms. Prerequisite: Psy 10.* A study of the psychological development of the individual within a context of biological, cultural, and social evolution. Not offered 1990–91. Instructor: Breger.

Psy 112. Abnormal Psychology. *9 units (3-0-6); third term. Prerequisite: Psy 12 or consent of instructor.* Continuation of material covered in Psy 12. The development of mental and emotional disturbances. Basic theory will be reviewed in relation to selected case material and relevant research. Instructor: Breger.

Psy 125. Reading and Research in Psychology. Same as Psy 25, but for graduate credit. *Not available for credit toward humanities-social science requirement.*

Lit/Psy 150. Psychoanalysis and Literature.* *9 units (3-0-6).* For course description, see Literature.

RUSSIAN *(See Languages)*

**Advanced courses with credit toward the 36-unit Humanities requirement. Other advanced courses receive credit toward the 36-unit H&SS requirement. See page 105.*

SOCIAL SCIENCE

PS/SS 12. Introduction to Political Science. *9 units (3-0-6).* For course description, see Political 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. Instructors: Davis, Hoffman, Kousser.

SS 33. Introduction to the Law. *9 units (3-0-6).* An introduction to Anglo-American law from both the legal and the social scientific points of view. Subject can vary from year to year. Available for introductory social science credit. Instructor: Strnad.

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).* Not available for social science credit unless specifically approved by social science faculty. Instructors: Staff, visiting lecturers.

Lin/SS 103. Psycholinguistics. *9 units (2-1-6).* For course description, see Linguistics.

Lin/SS 104. Sociolinguistics. *9 units (2-1-6).* For course description, see Linguistics.

Lin/SS 105. Computational Linguistics. *9 units (2-1-6).* For course description, see Linguistics.

PS/SS 116. War, Diplomacy, and International Politics. *9 units (3-0-6).* For course description, see Political Science.

SS 117. Problems of Urban Society. *9 units (3-0-6); third term.* Some significant urban problems of contemporary America, and alternative policies. Instructors: Staff.

PS/SS 119. The Politics of the Industrial State. *9 units (3-0-6).* For course description, see Political Science.

PS/SS 122. Noncooperative Games in Social Science. *9 units (3-0-6).* For course description, see Political Science.

PS/SS 123. Cooperation and Social Behavior. *9 units (3-0-6).* For course description, see Political Science.

PS/SS 125. Peasant Politics. *9 units (3-0-6).* For course description, see Political Science.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6).* For course description, see Economics.

SS 133. Topics in Anglo-American Law. *9 units (3-0-6); second, third terms.* 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. Instructors: Staff. *May be taken more than once if the topic is different.*

PS/SS 139. Comparative Politics. *9 units (3-0-6).* For course description, see Political Science.

SS 140 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3); first, second, third terms.* 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/SS 145. Public Finance. *9 units (3-0-6).* For course description, see Economics.

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.* Instructors: Staff and visiting lecturers.

SS 201. Game Theory. *9 units (3-0-6); second term. Prerequisite: Ma 112 a or equivalent.* Introduces utility theory, decision theory, and the theory of games, with emphasis on applications of the theory of games of incomplete information to modeling problems in the social sciences. Instructors: Border, Palfrey.

SS 202. Congress and the Executive. *9 units (3-0-6); third term.* Analysis of executive and congressional decision making. Emphasis on theory of committees and bureaucratic theory. Instructors: Kiewiet, McKelvey, Ordeshook.

SS 203. American Electoral Processes. *9 units (3-0-6); first term.* An in-depth analysis of American electoral processes with emphasis on the application of new theory and quantitative techniques. Instructors: Kousser, Kiewiet.

SS 204. Analytical Political Theory. *9 units (3-0-6); second term.* A survey of theoretical topics in social choice, voting, and electoral competition. Instructor: McKelvey.

SS 205. Microeconomic Theory I. *9 units (3-0-6); first term. Prerequisite: Ec 121 a or equivalent.* An introduction to economic theory and its applications. Problems in modeling and specification; maximization. Instructors: Border, Palfrey, Wilde.

SS 206. Microeconomic Theory II. *9 units (3-0-6); second term. Prerequisite: SS 205.* Classical consumption theory, the theory of production, markets, externalities, and the question of public goods. Instructors: Border, Ledyard.

SS 207. Microeconomic Theory III. *9 units (3-0-6); third term. Prerequisite: SS 206.* Modern economic theory, including decision theory, game theory, the role of uncertainty, and investment theory. Instructors: Border, Wilde.

SS 210 abc. Foundations of Political Economy. *9 units (3-0-6). Prerequisites: SS 204 and SS 206.* Mathematical theories of individual and social choice applied to problems of welfare economics and political decision making as well as 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: Ledyard, McKelvey, Ordeshook, Palfrey.

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: Ledyard, Palfrey, 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: Strnad, Wilde, Boessarts.

SS 213. Advanced Financial Economics. *9 units (3-0-6).* Theoretical financial economics at the graduate level. Core topics: mean-variance portfolio analysis, generalized measures of risk, the arbitrage pricing theory, intertemporal models, continuous-time portfolio selection, and option pricing. Additional topics, if time permits: stochastic calculus methods, advanced topics in option pricing, and the term structure of interest rates. Instructor: Strnad.

SS 214. The Economics of Regulation. *9 units (3-0-6); first term.* An analysis of government controls on prices, profits, entry, and product quality in the private sector, with special emphasis on the energy sector. Instructors: Staff.

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. Instructors: Staff.

SS 216. Interdisciplinary Studies in Law and Social Policy. *9 units (3-0-6).* 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. Instructors: Staff.

SS 222 abc. Econometrics. *9 units (3-0-6); first, second, third terms.* Regression analysis. Introduction to the use of multivariate and nonlinear methods in the social sciences. Students will be required to complete a major empirical project. Instructors: Dubin, Grether, El-Gamal.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6). Prerequisite: SS 222 ab; may be repeated for credit.* A course in quantitative methods for second- and third-year social science graduate students. Theory of identification and estimation of simultaneous equations system. Instructors: Dubin, Grether, El-Gamal, Hughson.

SS 228. Selected Topics in European Medieval History. *9 units (3-0-6).* The bibliography, sources, and methods of analysis appropriate for research on a variety of topics in medieval history, such as peasant life and production, organization of government, law and land tenure, demography, church-state relations, and history of mentalities. Instructor: Searle.

SS 229 abc. Theoretical and Quantitative Dimensions of Historical Development. *9 units (3-0-6); first, second, third terms. May be repeated for credit.* Introduction to modern quantitative history. The tools of economic and political theory applied to problems of economic, social, and political development in a historical context. Instructors: Davis, Hoffman, Kousser.

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. Instructor: Kiewiet.

SS 232 abc. Historical and Comparative Perspectives in Political Analysis. *9 units (3-0-6). Prerequisite: SS 204.* Provides a knowledge and understanding of developments in both the American past and in other parts of the world. Instructor: Kousser.

SS 234. Research Seminar in Modern Political Science. *9 units (3-0-6); may be repeated for credit.* Instructors: Staff.

SS 238. Optimal Control Theory in Economics. *9 units (3-0-6); first term. Prerequisite: Ec 121 a or equivalent.* The subject material of this course is the optimal control of dynamic economic systems with applications to resource extraction, limit pricing, research and development, and capital accumulation. Instructors: Staff.

SS 240. Techniques of Policy Research. *9 units (3-0-6); third term. Prerequisites: SS 205, SS 206.* The application of social science theory and methods to the formulation and evaluation of public policy. Instructor: Dubin.

SS 241 ab. Workshop in Policy Research. *9 units (3-0-6); first, second terms. Prerequisite: SS 240.* A working seminar in which the students and participating faculty apply the techniques examined in SS 240 to a policy problem of mutual interest. Instructors: Staff.

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.* Instructors: Staff.

Section Six

TRUSTEES, ADMINISTRATION, FACULTY

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(with date of first election)

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Audit Committee—S.R. Petersen, *Chairman;* D. Stanfill, *Vice Chairman;* T.E. Everhart, C.J. Medberry III, R.F. Mettler, S.R. Onderdonk, R.R. Von Hagen; *Advisory Members:* P.C. Jennings, D.W. Morrisroe

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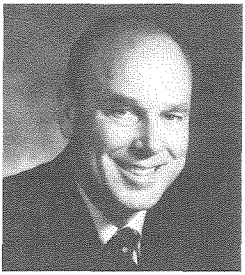
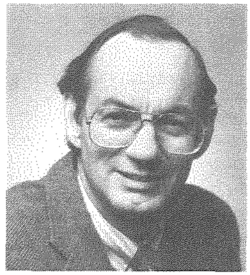


Thomas E. Everhart
President



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Theodore P. Hurwitz	*Vice President for Institute Relations*
Gary A. Lorden	*Vice President for Student Affairs*
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I. Bernice Slaughter	*Assistant to the Director of Admissions for Special Programs*
Sally J. Asmundson	*Director of Career Development*
Sheryl Mercer	*Assistant Director of Career Development*
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Sheryl Hayes	*Assistant Director of Financial Aid*
Daniel L. Bridges	*Director of Athletics and Physical Education*
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Institute Administrative Council (IAC)—T.E. Everhart, *Chairman;* J.N. Abelson, L. Allen Jr., F.C. Anson, D.R. Fowler, D.L. Goodstein, D.M. Grether, T.P. Hurwitz, P.C. Jennings, S.E. Koonin, G.A. Lorden, D.W. Morrisroe, G. Neugebauer, J.H. Seinfeld, D.J. Stevenson, E.C. Stone, M.L. Webster

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Vice Chairman: D.J. Kevles
Secretary: W. Whaling

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Term expires June 30, 1991	*Term expires June 30, 1992*	*Term expires June 30, 1993*
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N.R. Corngold	R.C. Flagan	D.B. Rutledge
G.R. Gavalas	E. Rothenberg	E.M. Stolper
H.A. Lester	W.L. Sargent	R.W. Gould
C.W. Peck	D.C. Van Essen	J.Z. Lee
J.H. Richards	D.B. Wales	J.H. Schwarz

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Term expires June 30, 1991	*Term expires June 30, 1992*
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A. Kuppermann	D.S. Cohen
A. Roshko	J.J. Hopfield

**Ex officio*

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Norman R. Davidson, *Executive Officer*
Paul H. Patterson, *Executive Officer*

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Derek H. Fender, Ph.D.
Biology and Applied Science
Norman H. Horowitz, Ph.D.
Biology
Edward B. Lewis, Ph.D.
Thomas Hunt Morgan Professor of Biology
Herschel K. Mitchell, Ph.D.
Biology
Ray D. Owen, Ph.D., Sc.D.
Biology
Roger W. Sperry, Ph.D., Sc.D., Nobel Laureate
Board of Trustees Professor of Psychobiology

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Biology
John M. Allman, Ph.D.
Hixon Professor of Psychobiology and Professor of Biology
Giuseppe Attardi, M.D.
Grace C. Steele Professor of Molecular Biology
Seymour Benzer, Ph.D., D.Sc.
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Charles J. Brokaw, Ph.D.
Biology
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Chemistry and Biology
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Norman Chandler Professor of Cell Biology
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Biology
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John J. Hopfield, Ph.D.
Roscoe G. Dickinson Professor of Chemistry and Biology
Masakazu Konishi, Ph.D.
Bing Professor of Behavioral Biology
Elias Lazarides, Ph.D.
Biology
Henry A. Lester, Ph.D.
Biology
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Biology
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Biology
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Albert Billings Ruddock Professor of Biology
Melvin I. Simon, Ph.D.
Ann P. and Benjamin F. Biaggini Professor of Biological Sciences
James H. Strauss, Ph.D.
Biology
David C. Van Essen, Ph.D.
Biology

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Biology
Mary B. Kennedy, Ph.D.
Biology
Ellen Rothenberg, Ph.D.
Biology
Barbara J. Wold, Ph.D.
Biology

[1] *Undergraduate Student Adviser*
[2] *Premedical Adviser*

Assistant Professors

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Biology
Pamela Bjorkman, Ph.D.[1]
Biology
James M. Bower, Ph.D.
Biology
William G. Dunphy, Ph.D.
Biology
Christof Koch, Ph.D.
Computation and Neural Systems
Gilles J. Laurent, Ph.D., D.V.M.
Biology and
Computation and Neural Systems
Howard Lipshitz, Ph.D.
Biology
Paul W. Sternberg, Ph.D.[1]
Biology
Mark A. Tanouye, Ph.D.
Biology
Kai Zinn, Ph.D.
Biology

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Roy J. Britten, Ph.D.[2]
Distinguished Carnegie Senior
Research Associate in Biology
R. Andrew Cameron, Ph.D.
Biology
Anne Chomyn, Ph.D.
Biology
Barbara R. Hough Evans, Ph.D.
Biology
Ellen G. Strauss, Ph.D.
Biology
Iwona T. Stroynowski, Ph.D.
Biology
Barbara S. Yancey, Ph.D.
Biology

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Bruce W. Birren, Ph.D.
Biology
Paul D. Boyer, Ph.D.
Biology
Susan E. Celniker, Ph.D.
Biology
Tien-Hsein Chang, Ph.D.
Biology
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Biology
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Biology
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Biology
Anna Glasgow, Ph.D.
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Biology
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Biology
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Biology
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Biology
Joan A. Kobori, Ph.D.
Biology
Richard J. Kuhn, Ph.D.
Biology
Akiko Kumagai, Ph.D.
Biology
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Applied Physics
Richard E. Doherty, B.S.
Computer Science
Charles Elachi, Ph.D.
Electrical Engineering and Planetary Science
Earl J. Freise, Ph.D.
Materials Science
Glen A. George, M.S.
Applied Science
David L. Johannsen, Ph.D.
Computer Science

[1]*von Kármán Instructor*
[2]*In residence 1989–90*

Michael Karyeaclis, Ph.D.
Applied Mechanics
Ilias G. Kastanas, Ph.D.
Applied Science
Romney R. Katti, Ph.D.
Electrical Engineering
Taras Kiceniuk, M.S.
Mechanical Engineering
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Mechanical Engineering
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Electrical Engineering
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Applied Mechanics
Roy S. Smith, Ph.D.
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Jet Propulsion
George T. Yates, Ph.D.
Mechanical Engineering

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Channing C. Ahn, Ph.D.[1]
Materials Science
Michael R. Brown, Ph.D.
Applied Physics
Hans J. Fecht, Ph.D.
Materials Science
Elzbieta Kolawa, Ph.D.
Applied Physics
Kai-Wei Nieh, Ph.D.[2]
Materials Science
Robert R. Snapp, Ph.D.[2]
Electrical Engineering
Eric F. Van de Velde, Ph.D.[3]
Applied Mathematics

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Henning Rosemann, Ph.D.
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Materials Science
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Senior Scientist
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Senior Scientist
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Senior Scientist
George T. Yates, Ph.D.
Senior Scientist

[1]*In residence 1989–90*

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Geophysics
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Geochemistry
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James H. Chen, Ph.D.
Geochemistry
G. Ed Danielson, M.S.
Planetary Science
Katherine Hutton, Ph.D.
Geophysics
Wayne F. Miller, B.S.
Geophysics
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Horace N. Gilbert, M.B.A., D.B.A.
Business Economics
William T. Jones, Ph.D.
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Robert W. Oliver, Ph.D.
Economics
Hallett D. Smith, Ph.D., L.H.D.
English
Alan R. Sweezy, Ph.D.
Economics

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History
Robert D. Wayne, M.A.
German

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Education
Charles Newton, Ph.B.
English

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Ronald L. Bush, Ph.D.
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Mary Stillman Harkness Professor of Social Science
Alan H. Donagan, B.Phil.
Doris and Henry Dreyfuss Professor of Philosophy
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J. O. and Juliette Koepfli Professor of the Humanities
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Political Science
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History and Social Science
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Economics and Social Sciences
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Literature
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Political Science
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Economics and Political Science
Charles R. Plott, Ph.D.
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Martin Ridge, Ph.D.[1]
History
Robert A. Rosenstone, Ph.D.
History
Thayer Scudder, Ph.D.
Anthropology
Eleanor M. Searle, D.M.S.
Edie and Lew Wasserman Professor of History

[1] *Part-time*

Annette J. Smith, Ph.D.
French
David R. Smith, Ph.D.
Literature
James F. Strnad II, J.D., Ph.D.[1]
Law and Economics
John A. Sutherland, Ph.D.
Literature
Frederick B. Thompson, Ph.D.
Applied Philosophy and Computer Science
Louis L. Wilde, Ph.D.
Economics

Associate Professors

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Economics
Jeffrey A. Dubin, Ph.D.
Economics
Philip T. Hoffman, Ph.D.
History and Social Science
James Z. Lee, Ph.D.
History
George W. Pigman III, Ph.D.
Literature
James F. Woodward, Ph.D.
Philosophy

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Mahmoud A. El-Gamal, Ph.D.
Economics
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History
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Philosophy
Eric N. Hughson, Ph.D.
Economics
Cindy Weinstein, Ph.D.
Literature

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Joss Lutz Marsh, Ph.D.
Literature
Nigel J. T. Thomas, Ph.D.
Philosophy

Ahmanson Postdoctoral Instructor

John R. Shepherd, Ph.D.
East Asian Studies

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History
Elazar Barkan, Ph.D.
History
Laird S. Boswell, Ph.D.
History
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H. Victor Neher, Ph.D., Sc.D.
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Mathematics
Olga Taussky Todd, Ph.D., D.Sc.h.c
Mathematics
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Mathematics
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Theoretical Physics
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[1]*Leave of absence 1990–91*

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Douglas L. Ulmer, Ph.D.
Mathematics

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Richard P. Mount, Ph.D.
Physics
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Radio Astronomy
Anneila I. Sargent, Ph.D.
Astronomy
Ryszard Stroynowski, Doctorat
Physics
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Physics

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Ming-Chung Chu, Ph.D.
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Vitaly Efimov, Ph.D.
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Gerald Eigen, Ph.D.
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Astrophysics
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Physics
James R. Graham, Ph.D.
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John M. Grunsfeld, Ph.D.
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Astrophysics
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Physics

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Concurrent Computation
Emmanuel Bonvin, Ph.D.
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Physics
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Astrophysics
Anna Ceresole, Ph.D.
Theoretical Physics
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Physics
Scott Tremaine, Ph.D.
Theoretical Astrophysics

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Mathematics
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Mathematics
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Physics
Marlies Gerber, Ph.D.
Mathematics
Ilias G. Kastanas, Ph.D.
Mathematics

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Physics
Thomas E. Faber, Ph.D.
Physics
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Physics
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Mathematics
Shijie Gu
Physics
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Astronomy
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Physics
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Physics
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Physics
Harding E. Smith, Ph.D.
Physics
H. Michael Sommermann, Ph.D.
Physics

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Physics
Franciscus W. M. Verbunt, Ph.D.
Physics
Maddali Vivekanand, Ph.D.[1]
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Physics
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David P. Woody, Ph.D.
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Director of Counseling Services
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Jacqueline Miles, Ph.D.
Institute Psychologist
Jon-Patrik Pedersen, Ph.D.
Institute Psychologist
Daniel Sherman, Ph.D.
Institute Psychologist

Human Relations Adviser

Position open. Search in progress.

Industrial Relations Center

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Director

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Institute Archivist, Faculty Associate
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Head, Humanities and Social Sciences Libraries
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Assistant Laboratory Director, Engineering and Review

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Chamber Music Program
William Bing
Instrumental Music Director and Chamber Music Program
James Boyk
Interpretive Music Class
Donald Caldwell
Director of Men's Glee Club
Darryl Denning
Classical and Flamenco Guitar Class
Allen Gross
Symphony Orchestra Director
Monica Hubbard
Director of Women's Glee Club
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Director of Theater Arts

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* * * *

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* * * *

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