Areas of Study and Research

AEROSPACE

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

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

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

- *Physics of Fluids.* Fluid dynamics as a discipline is as much a part of physics as of engineering. Physics of fluids refers to research in areas closer to applied physics than to direct technical applications. Present active research includes studies in gas dynamics and hypervelocity flows, diffraction and focusing of shock waves, detonation waves, shock-induced Rayleigh-Taylor and Richtmeyer-Meshkov instabilities, and transient supersonic jets, the development of laser-scattering diagnostic techniques for fluid-flow measurements, the study of structures and mechanics in transition and turbulence, studies of two-phase flows and turbulent mixing and experimental manipulation and control of wall-bounded flows for improved flow characteristics, such as reduction of drag, noise, and structural loading.

- *Physics of Solids and Mechanics of Materials.* Mechanics of materials research involves both the quasi-static and dynamic characterization of the mechanical behavior and failure of solids. In order to understand materials for applications in a wide range of structures germane to aerospace as well as other engineering disciplines, both the physical foundations of that behavior and the mathematical or numerical representation of such behavior needs to be understood. Accordingly, studies involve material response at both the macroscopic (continuum) scales and the micro- and nanoscales. Of interest are the typical engineering metals, multiphase (composite) materials, polymers and ceramics, thin film materials used in microelectronic and optoelectronic applications, soft tissue mechanics of materials, and active materials used in structural actuation and controls. Other areas of active research include the study of highly nonlinear dynamics in solids, multiscale acoustic metamaterials, and nondestructive evaluation/structural health monitoring (NDE/SHM) of structures.
- *Space Technology.* The industrial utilization and exploration of space must address a wide range of engineering problems. Examples of research activities include lightweight structures for large aperture systems, in-space manufacturing, material and structural behavior in extreme temperature and radiation environments, spacecraft shielding against hypervelocity impact threats, the mechanics of sample containment for planetary protection, low-g biomechanics, biomimetics of locomotion in planetary atmospheres, hypersonic reentry into planetary atmospheres, in-space propulsion, guidance, navigation and control, and launch-vehicle performance and safety. Opportunities exist for research in collaboration with the Jet Propulsion Laboratory.
- *Computational Solid Mechanics.* Computational solid mechanics addresses phenomena ranging from the atomistic scale, e.g., nanoindentation, to the structural scale, e.g., fracture of aircraft or spacecraft components, modeling of large space structures or even dynamic fragmentation phenomena accompanying hypervelocity impact. It provides an indispensable tool for understanding the relation between structure and mechanical properties of materials, for predicting the efficiency of such industrial processes as machining and metal forming, and for assessing the safety of such structures as airplanes, spacecraft, automobiles, and bridges. The goals and objectives of this activity are to provide a state-of-the-art environment for the development of numerical methods in solid mechanics, to provide the computational resources required for large-scale simulations in solid mechanics, and to serve as an instructional facility for advanced courses.

- *Computational and Theoretical Fluid Dynamics.* Many of the subjects studied experimentally at GALCIT are also being investigated by numerical simulation and by theoretical analysis. Present active research areas in computational and theoretical techniques include direct numerical simulation, particle methods for flow simulation, new algorithms and subgrid-scale models for compressible and incompressible flows, large-eddy simulation methods, flows with shocks and driven by shocks, analytical and computational techniques for turbulence structure diagnostics, analysis of turbulent mixing dynamics, high-explosive interactions with deformable boundaries, and detailed chemical reaction kinetics in flames and detonations.
- *Mechanics of Fracture.* An active effort is being made to understand mechanisms in a wide range of fracture problems. Aspects that are studied include quasi-static and dynamic crack growth phenomena in brittle and plastically deforming solids, polymers and advanced composites, as well as fatigue and failure of adhesive bonds. Research areas adjunct to dynamic fracture studies are those of dynamic localization in metals and of failure in frictional interfaces. These include the study of shear rupture phenomena in both coherent and incoherent interfaces. The dynamic failure of modern composite and layered materials and the phenomenon of earthquake rupture growth along geological faults have motivated these studies.
- *Aeronautical Engineering and Propulsion.* Research in the aeronautical engineering area includes studies of airplane trailing vortices and separated flows at high angles of attack. Research work in the propulsion area has centered on the fluid dynamic problems associated with combustion, solid propellant rocket motor instabilities, fluid dynamics and optimization of scramjets, and pulse detonation engines.
- *Biomechanics of Fluids and Solids.* The kinematics and dynamics of fluid flows in biological systems are studied in experiments, numerical simulations, and theoretical analyses. These flows are often characterized by unsteady vortex dynamics, coupled fluid interactions with flexible material surfaces, non-Newtonian fluid behavior and, in some cases, compressibility. Areas of active research include animal swimming and flying, cardiovascular fluid dynamics and hemodynamics, the mechanics of morphing/active deformable surfaces for flow control, and biologically inspired design of engineering systems.
- *Technical Fluid Mechanics.* These areas are related to a variety of modern technological problems and, in addition, to the traditional aeronautical problems of drag, wing stall, and shear flow mixing. Additional areas of activity include bluff-body aerodynamics, fluid-structure interaction, turbulent combustion, laminar diffusion flames and their instabilities, explosions, hydrodynamics and two-phase flows, interaction of vorticity

with free-surface, cardiac flows, swimming and flying, and active and passive control of transition and turbulence. Acoustics problems studied include jet noise, combustion noise, and instabilities such as the generation of organ pipe oscillations in large burners of electric generating plants.

- *Fluid Mechanics, Control, and Materials.* The effects of boundary conditions on turbulence characteristics and general flow physics, scaling and controllability, interdisciplinary methods based on developments in materials science and control techniques. Manipulation of canonical and simple model flows to probe fundamental issues of flow physics and control. Development of smart, biomimetic boundaries. Development of practical control and measurement techniques and devices. Experimental study of wall-bounded turbulence for scalability of control from the lab to large-scale applications.
- *Mechanics of Lightweight Space Structures.* Current efforts in the field of next-generation deployable space structures aim to increase reliability and also lower fabrication and assembly costs by moving toward structures that consist of only a small number of separate pieces able to undergo large elastic deformations. These elastic-stored-energy structures return to their original, unstressed configuration when they are released in orbit. The design of these structures requires accurate structural models that incorporate geometry change and contact effects in sufficient detail to capture the actual behavior that is observed in ground tests. Local and global instabilities are often observed during folding/deployment, and their effects can also be very important. Ultimately, validation against space-based experiments will be pursued for a selected number of structural configurations. In parallel to these studies, thermomechanical constitutive models for ultrathin composite materials for these novel deployable space structures are being developed. Extensive studies of the deployment, elastic, and viscoelastic stability of stratospheric balloons are also being conducted.

Physical Facilities

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

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

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

APPLIED AND COMPUTATIONAL MATHEMATICS

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

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

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

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

Areas of Research

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

APPLIED MECHANICS

Areas of Research

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

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

Physical Facilities

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

APPLIED PHYSICS

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

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

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

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

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

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

Areas of Research and Physical Facilities

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

ASTROPHYSICS

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

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

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

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

Areas of Research

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

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

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

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

Physical Facilities

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

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

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

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

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

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

BEHAVIORAL AND SOCIAL NEUROSCIENCE

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

Areas of Research

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

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

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

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

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

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

mental principles of chemical bonding and molecular energetics, by which a given linear sequence of amino acids folds into a specific three-dimensional structure in the appropriate cellular environment; how electrons move within a cell to accomplish the many redox reactions necessary for life; how light is harvested by photopigments and is perceived in vision; the function of integral membrane proteins in energy and signal transduction processes; and the mechanisms by which enzymes both efficiently and specifically catalyze biochemical interconversions. This fundamental understanding of the molecular basis of biological processes provides a powerful base for the development of applications in medicine, including biotechnology and rational drug design, and in the chemical industry, where nucleic acids, proteins, and their analogs are now being used in the development of chemical systems for novel applications, and where mutagenesis and selection systems are used to produce novel materials.

BIOENGINEERING

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

Areas of Research

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

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

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

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

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

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

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

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

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

BIOLOGY

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

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

Areas of Research

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

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

A geobiology option is described in the Geological and Planetary Sciences section.

Physical Facilities

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

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

BIOTECHNOLOGY

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

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

CHEMICAL ENGINEERING

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

Areas of Research

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

- *Biological Design and Engineering.* Engineering of proteins and metabolic pathways by computational and laboratory evolution approaches. Biocatalysis for sustainable "green" production of pharmaceuticals and specialty chemicals. Engineering organisms to convert biomass to fuels and chemicals.
- *Fluid Mechanics and Transport Processes.* Mechanics of polymeric liquids, microstructured fluids, colloidal dispersions, and suspensions and granular media. Transport in heterogeneous media.
- *Polymer Physics and Chemistry.* Molecular understanding of polymer melt rheology. Optical properties of polymer blends. Dynamic modeling of polymer structure and rheology. Synthesis of tailored polymers by chemical and biological means.
- *Biomaterials.* Synthesis and properties of organic materials designed for use in living systems. Therapeutic modification of existing systems.
- *Cellular Engineering.* Quantitative analysis and redesign of molecular events governing cell behavior.
- *Catalysis and Biocatalysis.* Synthesis of molecular sieves and organic-inorganic hybrid materials. Synthesis of inorganic membranes for gas separations and catalysis. Biological routes to the synthesis of chemicals.
- *Electronic Materials and Devices.* Plasma processing of semiconductors, pattern etching and deposition. Modeling and simulation of pattern-dependent effects. Chemical reaction dynamics of plasma-surface interactions.
- *Microplasmas.* Sources of reactive radicals and ions at high pressures. Microreactors for gas conversion/pollutant destruction. Synthesis of nanocrystals. VUV-excimer radiation emitters.
- *Nanotechnology.* Aerosol synthesis of nanoparticles for microelectronic and photovoltaic applications. Nanoprobes, nanomechanics, nanofluidics. Crystallization in carbon nanotube cavities. Synthesis and characterization of quantum dots and nanostructural materials. Environmental consequences of nanotechnology.
- *Environmental Chemical Engineering.* Physics and chemistry of atmospheric gases and aerosols, bioaerosols, climate change.
- *Aerosols and Colloids.* Nucleation and growth of particles. Particle formation and reactions. Structure and properties of colloidal dispersions. Aerosol and colloidal particle characterization.
- *Applied Mathematics and Computational Physics.* Supercomputer applications in fluid mechanics and environmental modeling. Concurrent computing. Asymptotic analyses of transport processes.
- *Physics of Complex Fluids.* Structures, phase transitions, and dynamics of polymers, liquid crystals, surfactant solutions, and suspensions.

- *Materials for Energy Technologies.* Electrochemistry of fuel cells. Ion transport through solids. Design of thermoelectric materials.

Physical Facilities
The chemical engineering laboratories, mainly housed in the Eudora Hull Spalding Laboratory of Engineering and the Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering (scheduled to open in early 2010), are well equipped. The facilities include experimental reactors, computational facilities, NMR spectrometers, and numerous special research equipment for molecular simulations, DNA synthesis, and electronic, optical, and chemical measurements.

CHEMISTRY

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

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

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

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

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

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

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

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

Physical Facilities
The laboratories of chemistry consist of eight units providing space for about 25 research groups, including 300 graduate students and postdoctoral research fellows. Crellin and Gates Laboratories house several research groups, the divisional instrumentation facilities, and the divisional administrative offices. Synthetic research groups occupy the Arnold and Mabel Beckman Laboratory of Chemical Synthesis and Church Laboratories. The Braun Laboratories and the Broad Center for the Biological Sciences house biochemical groups and are shared with the Division of Biology. The Arthur Amos Noyes Laboratory of Chemical Physics is one of the major research facilities for chemical physics and inorganic chemistry and is adjoined by the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory. Chemistry groups will soon join several chemical engineering colleagues in the nearly completed Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering. A number of resource centers serving researchers of the division are located in the Beckman Institute.

CIVIL ENGINEERING

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

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

Areas of Research
Graduate work leading to advanced degrees lies chiefly in the following fields: structural engineering and structural dynamics; applied mechanics; earthquake engineering; finite element analysis; and environmental engineering (see also environmental science and engineering). In the past few years, graduate students and members of the faculty have pursued a variety of research programs, including the analysis of structures subjected to earthquakes and other dynamic loadings; optimal performance-based structural design;

system identification and control of structures; structural health monitoring; the use of finite element methods for structural analysis; and seismic risk and structural reliability.

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

Physical Facilities

Civil engineering activities are housed in two buildings: the Franklin Thomas Laboratory, which contains the earthquake engineering research laboratory and the vibration laboratory; and the W. M. Keck Engineering Laboratories, which contains the environmental science and engineering laboratories. Excellent computing facilities are available through the campus computing network and in the specialized computing centers of various research groups.

COMPUTATION AND NEURAL SYSTEMS

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

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

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

Areas of Research

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

COMPUTER SCIENCE

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

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

Areas of Research

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

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

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

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

Physical Facilities
The computer science department has excellent computing facilities ranging from high-performance workstations to multiprocessors and supercomputers. The department maintains a large computer lab open to students, and offers a large collection of software for a wide range of applications. The inventory of computers and graphics cards is frequently upgraded, and students have easy access to state-of-the-art equipment. The Institute libraries maintain a large collection of journals in computer science and related fields.

CONTROL AND DYNAMICAL SYSTEMS

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

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

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

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

Areas of Research

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

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

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

ELECTRICAL ENGINEERING

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

Areas of Research and Physical Facilities

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

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

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

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

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

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

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

ing; capacity computations for wireless channels; channel estimation, identification, and equalization; multiple-antenna systems and diversity techniques; space-time codes; modulation techniques; channel access and spectral sharing through various TDMA, FDMA, CDMA, and hybrid techniques; multiuser detection and interference cancellation; dynamic channel allocation; models and performance analysis of wireless networks; ad hoc networks; signal processing for wireless. The research encompasses various areas of information theory, coding theory, stochastic processes, statistical and adaptive signal processing, and network theory.

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

ENERGY SCIENCE AND TECHNOLOGY

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

ENVIRONMENTAL SCIENCE AND ENGINEERING

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

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

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

Areas of Research

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

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

Physical Facilities

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

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

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

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

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

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

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

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

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

GEOLOGICAL AND PLANETARY SCIENCES

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

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

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

Physical Facilities

The division is housed in four adjacent buildings, which are well equipped for modern instruction and laboratory work. They contain several seminar rooms and a library as well as student and faculty offices. Numerous computers are distributed throughout the division, including a facility for geographic information systems and remote sensing. Many efforts within the division-related geodetic, geological, and seismological investigation and monitoring of plate boundary regions are coordinated through the Caltech Tectonics Observatory. The division operates a 512-node (4096 core) supercomputer used by students and faculty for Earth and planetary science studies. Rock and mineral collections and sample preparation areas are available. There are modern laboratories equipped with a scanning electron microscope and electron microprobe; a variety of plasma-source, gas-source, thermal emission, and secondary ion mass spectrometers; tunable laser spectrometers; high-temperature furnaces and high-pressure apparatus including piston-cylinder, multi-anvil, diamond anvil, and shock-wave facilities. Our most advanced analytical tools are operated by our Center for Cosmochemical and Geochemical Microanalysis. Cooperation with other departments on campus, such as materials science and environmental science and engineering, provides access to additional instrumentation for sample preparation and analysis.

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

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

HISTORY AND PHILOSOPHY OF SCIENCE

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

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

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

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

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

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

Areas of Research

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

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

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

INDEPENDENT STUDIES PROGRAM

Independent Studies is an educational alternative for undergraduates whose goals cannot be satisfied with a normal undergraduate option. The student gathers a three-person faculty committee, representing at least two divisions of the Institute, and chooses his or her own scholastic requirements under this committee's supervision. Approval must also be obtained from the Curriculum Committee, a standing committee of the faculty. The independent studies program has no facilities of its own. Areas of study and research may be selected from any part of the Institute. (For a complete description see page 223.)

INFORMATION SCIENCE AND TECHNOLOGY

Information Science and Technology (IST) is a multidivisional research area that includes participants from the Divisions of Biology, Chemistry and Chemical Engineering, Engineering and Applied Science, Humanities and Social Sciences, and Physics, Mathematics and Astronomy. Areas of emphasis include networking and distributed systems, neuromorphic engineering and sensory-based machines, quantum computation and communications, molecular electronics and biochemical computing, biological circuit design, information flow in economic and social systems, and mathematical foundations of information.

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

MATERIALS SCIENCE

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

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

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

MATHEMATICS

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

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

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

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

MECHANICAL ENGINEERING

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

The educational program in mechanical engineering at Caltech prepares students for professional practice and research in an era of rapidly advancing technology. It combines a strong background in the basic and engineering sciences with laboratory and design experience. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Areas of Research

- *Mechanics of Materials.* Studies in the field of mechanics of materials are an integral part of the mechanical engineering option. In general, work pursued within the mechanical engineering option emphasizes aspects of mechanics that are concerned with mechanical behavior of homogeneous and heterogeneous solids, bridging temporal and spatial scales, thin film, MEMS, active materials, composites, dynamic deformation, fracture and frictional sliding of solids, computational modeling, and advanced experimental diagnostic techniques. Additional interests include the mechanics of heterogeneous geological systems.
- *Mechanical Systems and Engineering Design.* Activities in these areas encompass a broad range of traditional mechanical engineering fields, including control systems, dynamics, kinematics, and mechanical design, as well as cross-disciplinary areas such as signal processing, computer control, engineering computation, electromechanical design, micro-electro-mechanical systems (MEMS) design, and bioengineering. General areas of interest include design theory and methodology, imprecision in engineering design, engineering system design, MEMS design, kinematics, robotics, autonomous systems, control of mechanical systems, computer-aided design, and simulation.
- *Thermal Systems and Fluid Dynamics.* This area encompasses a broad spectrum of research activities, including convective heat transfer (packed beds, moving granular media, rotating flows), chemical vapor deposition of thin films, computational fluid dynamics including molecular dynamic simulations, acoustics of turbulent flows, explosion dynamics including deflagrations, detonations, and shock waves, two-phase flow including colloidal dispersions, cavitation, turbomachines for flow of liquids and rocket propellants and combustion, and transport phenomena in micro/nanofluidic systems including phase transitions, fluid instabilities in free surface flows, and Marangoni and thermocapillary forcing in thin liquid films.

Physical Facilities

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

PHYSICS

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

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

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

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

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

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

  The infrared astronomy groups studies a host of astrophysical phenomena using Caltech's Palomar Observatory, the twin 10-meter optical telescopes at the Keck Observatory, and observations from the Spitzer Space Telescope. Caltech also manages the Spitzer Science Center on campus.
- *Theoretical Astrophysics.* The TAPIR (Theoretical Astrophysics Including Relativity) group carries out research on an ever-changing list of topics, including high-energy astrophysics and the physics of black holes and neutron stars, gravitational-wave astrophysics, cosmology, the formation of stars and galaxies in the early universe, and general relativity.
- *Cosmology*. The observational cosmology group explores the structure and dynamics of the early universe using precise measurements of the cosmological microwave background radiation from detectors on the ground, on balloons, and on spacecraft. Efforts to directly detect dark matter are also underway. These experiments include an active program of detector development in collaboration with scientists at the Jet Propulsion Laboratory. Theoretical studies seek to understand the large-scale structure of the universe, including the physical nature of dark matter and dark energy.
- *Gravitational-wave Astronomy.* Observations from the LIGO and LISA projects seek to use gravitational radiation to study a vari-

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

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

Physical Facilities

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

SOCIAL SCIENCE

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

Areas of Research

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

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

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

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

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