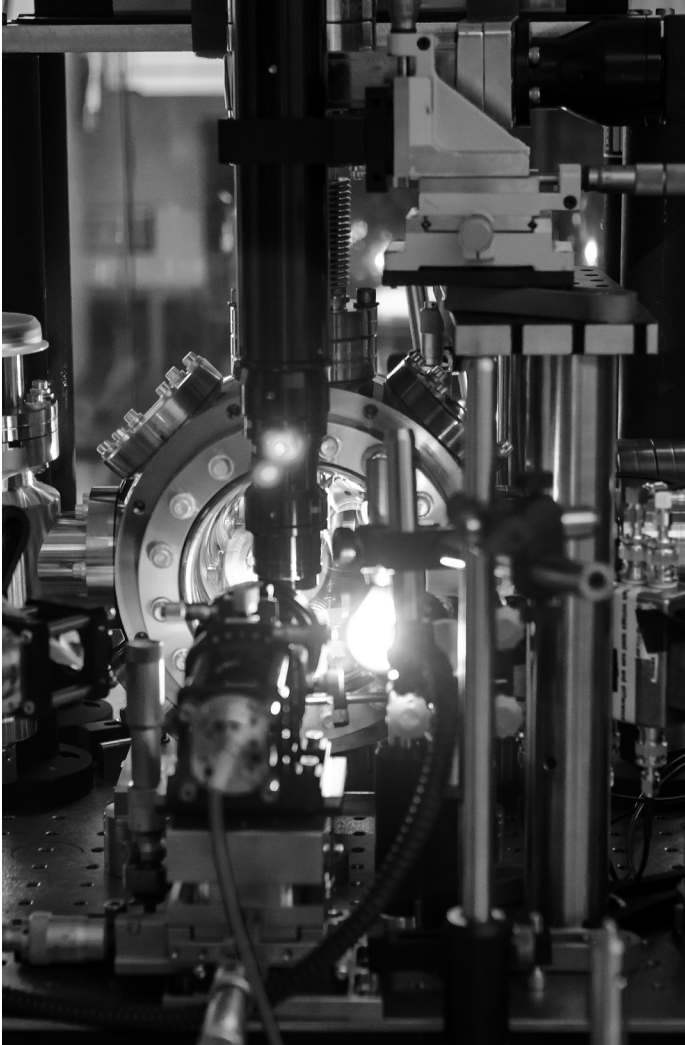


Areas of Study and Research



AEROSPACE

The Guggenheim Aeronautical Laboratory, the Kármán Laboratory of Fluid Mechanics and Jet Propulsion, and the Firestone Flight Sciences Laboratory form the Graduate Aerospace Laboratories, widely known as GALCIT. In this complex are housed the solid mechanics, impact mechanics, and deployable space structures laboratories, the hypersonics and hydrodynamics facilities, the explosion dynamics and detonation physics laboratories, and the Joe and Edwina Charyk Laboratory of Bioinspired Design and Biopropulsion, the Center for Autonomous Systems and Technologies, as well as the various disciplines making up the broad field known as aerospace.

Areas of Research

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

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

- ***Mechanics of Lightweight Space Structures.*** Current efforts in the field of next-generation deployable space structures aim to increase reliability and also lower fabrication and assembly costs by moving toward structures that consist of only a small number of separate pieces able to undergo large elastic deformations. These elastic-stored-energy structures return to their original, unstressed configuration when they are released in orbit. The design of these structures requires accurate structural models that incorporate geometry change and contact effects in sufficient detail to capture the actual behavior that is observed in ground tests. Local and global instabilities are often observed during folding/deployment, and their effects can also be very important. Ultimately, validation against space-based experiments will be pursued for a selected number of structural configurations. In parallel to these studies, thermomechanical con-

stitutive models for ultrathin composite materials for these novel deployable space structures are being developed. Extensive studies of the deployment, elastic, and viscoelastic stability of stratospheric balloons are also being conducted.

- **Physics of Fluids.** Fluid dynamics as a discipline is as much a part of physics as of engineering. Physics of fluids refers to research in areas closer to applied physics than to direct technical applications. Present active research includes studies in gas dynamics and hypervelocity flows, diffraction and focusing of shock waves, detonation waves, shock-induced Rayleigh-Taylor and Richtmeyer-Meshkov instabilities, transient supersonic jets, the development of laser-scattering diagnostic techniques for fluid-flow measurements, the study of structures and mechanics in transition and turbulence, studies of two-phase flows and turbulent mixing, chemically reacting flows, and experimental manipulation and control of wall-bounded flows for improved flow characteristics, such as reduction of drag, noise, and structural loading.
- **Physics of Solids and Mechanics of Materials.** Mechanics of materials research involves both the quasi-static and dynamic characterization of the mechanical behavior and failure of solids. In order to understand materials for applications in a wide range of structures germane to aerospace as well as other engineering disciplines, both the physical foundations of that behavior and the mathematical or numerical representation of such behavior needs to be understood. Accordingly, studies involve material response at both the macroscopic (continuum) scales and the micro- and nanoscales. Of interest are the typical engineering metals, multiphase (composite) materials, polymers and ceramics, thin film materials used in microelectronic and optoelectronic applications, soft tissue mechanics of materials, and active materials used in structural actuation and controls. Other areas of active research include the study of highly nonlinear dynamics in solids, multiscale acoustic metamaterials, the analysis and design of mechanical metamaterials for the extreme conditions in air and space applications, and nondestructive evaluation/structural health monitoring of structures.
- **Space Technology.** The goal of industrial utilization and exploration of space requires that one addresses a wide range of engineering problems. Examples of research 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., nanostructured materials or nanoscale structures and devices, to the structural scale, e.g., fracture of aircraft or spacecraft components, modeling of large space structures or even dynamic fragmentation phenomena accompanying hypervelocity impact. It provides an indispensable tool for understanding the relation between structure and mechanical properties of materials, for predicting the efficiency of such industrial processes as machining and metal forming, and for assessing the safety of such structures as airplanes, spacecraft, automobiles, and bridges. The goals and objectives of this activity are to provide a state-of-the-art environment for the development of numerical methods in solid mechanics, to provide the computational resources required for large-scale simulations in solid mechanics, and to serve as an instructional facility for advanced courses.
- **Computational and Theoretical Fluid Dynamics.** Many of the fluid dynamics phenomena studied experimentally at GALCIT are also being investigated by numerical simulation and by theoretical analysis. Present active research areas in computational and theoretical techniques include direct numerical simulation, particle methods for flow simulation, new algorithms and sub-grid-scale models for compressible and incompressible flows, large-eddy simulation methods, flows with shocks and driven by shocks, analytical and computational techniques for turbulence structure diagnostics, analysis of turbulent mixing dynamics, high-explosive interactions with deformable boundaries, chemically reacting flows, and detailed chemical reaction kinetics in flames and detonations.
- **Mechanics of Fracture.** An active effort is being made to understand mechanisms in a wide range of fracture problems. Aspects that are studied include quasi-static and dynamic crack growth phenomena in brittle and plastically deforming solids, polymers and advanced composites, as well as fatigue and failure of adhesive bonds. Research areas adjunct to dynamic fracture studies are those of dynamic localization in metals and of failure in frictional interfaces. These include the study of shear rupture phenomena in both coherent and incoherent interfaces. The dynamic failure of modern composite and layered materials and the phenomenon of earthquake rupture growth along geological faults have motivated these studies.
- **Aeronautical Engineering and Propulsion.** Research in the aeronautical engineering area includes studies of airplane trailing vortices and separated flows at high angles of attack. Research work in the propulsion area has centered on the fluid dynamic problems associated with combustion, solid propellant rocket motor instabilities, fluid dynamics and optimization of scramjets, and pulse detonation engines.
- **Biomechanics of Fluids and Solids.** The kinematics and dynamics of fluid flows in biological systems are studied in

experiments, numerical simulations, and theoretical analyses. These flows are often characterized by unsteady vortex dynamics, coupled fluid interactions with flexible material surfaces, non-Newtonian fluid behavior, and, in some cases, compressibility. Areas of active research include animal swimming and flying, cardiovascular fluid dynamics and hemodynamics, the mechanics of morphing/active deformable surfaces for flow control, and biologically inspired design of engineering systems.

- **Technical Fluid Mechanics.** These areas are related to a variety of modern technological problems and, in addition, to the traditional aeronautical problems of drag, wing stall, and shear flow mixing. Additional areas of activity include bluff-body aerodynamics, fluid-structure interaction, turbulent combustion, laminar diffusion flames and their instabilities, explosions, hydrodynamics and two-phase flows, interaction of vorticity with free-surface, cardiac flows, swimming and flying, and active and passive control of transition and turbulence. Acoustics problems studied include jet noise, combustion noise, and instabilities such as the generation of organ pipe oscillations in large burners of electric generating plants.
- **Fluid Mechanics, Control, and Materials.** The effects of boundary conditions on turbulence characteristics and general flow physics, scaling and controllability are investigated using interdisciplinary methods based on developments in materials science and control techniques. Experimental manipulation of canonical and simple model flows is used to probe fundamental issues of flow physics and control.
- **Autonomous Systems and Technologies.** Interdisciplinary research in the expanding area of autonomous systems involves, but are not limited to, drones, robots, and spacecraft for use in science, exploration, and transportation. The research addresses sensing, control, vision, machine learning, and other emerging areas. Advanced drone research, autonomous exploration, and swarm robotics will draw research from the full range of engineering at Caltech, the geological and planetary sciences division, and JPL.

Physical Facilities

The Graduate Aerospace Laboratories contain a diversity of experimental facilities in support of the programs described above. The Cann Laboratory is a teaching facility utilized for graduate and undergraduate experiments in fluid and solid mechanics. Low-speed wind tunnels include the John W. Lucas Adaptive Wall Tunnel, the Merrill Wind Tunnel, and special-purpose flow facilities. Smaller water channels and a tow tank for studies of wave motion and flow visualization are also available. For investigations of high-speed flows, there is a Ludwig tube, a supersonic shear layer facility, a hypervelocity expansion tube, and the T5 shock tunnel for studying hypervelocity gas flows up to 7 km/s. Shock tubes and other special facilities are available for the study of extreme temperatures, shock waves, deflagrations, detonations acoustics, and combustion at variable pressure conditions.

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

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

Other assets include state-of-the-art electronic instrumentation and computer systems for real-time control of experiments, data acquisition, processing, storage, and digital image processing. Computational facilities include powerful workstations, on-campus high-performance computing machines, and remote supercomputers such as those generally available at NSF, NASA, and DOE centers. Graphics workstations are available to support research in computational fluid dynamics and solid mechanics.

APPLIED AND COMPUTATIONAL MATHEMATICS

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

In addition to the applied and computational mathematics faculty, professors from other disciplines such as mathematics, physics, engi-

neering, and biology supervise research and offer courses of special interest. The applied and computational mathematics group has access to supercomputers and concurrent computers.

The present graduate program is one leading mainly to the Ph.D. degree. The curriculum consists of two types of courses: those that survey the methods used in applied and computational mathematics, and those that have a special applied and computational mathematics flavor and represent active research interests of the members of the faculty. Among the latter have been wave motion, perturbation theory, fluid mechanics, optimization, stochastic processes, wavelet analysis, signal processing, numerical analysis, computational electromagnetism, computational fluid dynamics, mathematics of data science, probability, random matrix theory, applied algebraic geometry and statistical inference, game and decision theoretic approaches to numerical approximation and learning, homogenization, multifidelity and multiscale analysis, and stochastic modeling, stochastic analysis, data assimilation, and inverse problems. Through study outside of applied and computational mathematics, each student is expected to become competent in some special physical or nonmathematical field. In this way, subjects for research appear naturally, and a broad educational program is provided.

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

Areas of Research

Research is particularly strong in theoretical and computational fluid mechanics, theoretical and computational materials science, computational electromagnetism, numerical analysis, ordinary and partial differential equations, multi-scale analysis, geometric integration, integral equations, linear and nonlinear wave propagation, water waves, bifurcation theory, perturbation and asymptotic methods, stability theory, variational methods, approximation theory, uncertainty quantification, randomized algorithms, continuous optimization, discrete optimization, statistical estimation, computational harmonic analysis, stochastic processes, signal and imaging processing, inverse problems, mathematical biology, large-scale scientific computing, mathematics of data science, and probability and random matrix theory, game and decision theoretic approaches to numerical approximation and learning, homogenization, multifidelity and multiscale analysis, and stochastic modeling and stochastic analysis, data assimilation, inverse problems, and related branches of analysis.

APPLIED MECHANICS

Areas of Research

Advanced instruction and research leading to degrees of Master of Science and Doctor of Philosophy in applied mechanics are offered in

such fields as elasticity; plasticity; wave propagation in solid media; mechanics of quasi-static and dynamic fracture; dynamics and vibrations; finite element analysis; and stability, control, and system identification of mechanical and structural systems. Research studies in these areas that illustrate current interests include linear and nonlinear random vibrations of uncertain dynamical systems; structural dynamics and control for earthquake and wind loads; linear and nonlinear problems in static and dynamic elasticity, plasticity, and viscoelasticity; computational mechanics; mechanics of time-dependent fracture; chaotic behavior of dynamical systems; and material instabilities and phase transformations in solids.

Physical Facilities

In addition to the regular facilities in the Division of Engineering and Applied Science, which include extensive computing facilities, certain special facilities have been developed in connection 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. The earthquake engineering research laboratory contains specialized equipment for vibration tests of buildings, dams, and other structures, and for the recording and analysis of strong-motion earthquakes. Solid mechanics laboratories contain extensive testing equipment for the study of fracture and structural failure. Excellent computing facilities are available through the campus computing network and in the specialized centers of various research groups.

APPLIED PHYSICS

The Applied Physics option was instituted in 1970 in order to provide an interdivisional program for undergraduate and graduate students at Caltech interested in the study of both pure and applied physics. The small size of Caltech, coupled with its strength in the basic sciences and engineering, has made it possible for faculty and students alike to pursue wide-ranging interests in the application of modern physics to the development of new technology. Research efforts in applied physics are driven by a fundamental understanding of the physical principles underlying applications and a strong motivation to use this knowledge to invent new experimental techniques, processes, devices and materials. Core and affiliate faculty spanning several divisions on campus participate in instruction and research leading to B.S., M.S., and Ph.D. degrees in applied physics.

This program is designed for undergraduate and graduate students who wish to expand their training beyond the study of fundamental physics to include research and development of real-world applications. The training helps develop a solid foundation in physics through introductory courses in classical physics, classical electrodynamics, quantum mechanics, thermodynamics, statistical mechanics, and mathematical physics. More advanced training is provided through coursework and research activities in solid state physics, electromagnetic wave propa-

gation, optoelectronic materials and devices, transport phenomena in hydrodynamic and condensed matter systems, plasma physics, biological physics, semiconductor principles and devices, quantum electronics, and low-dimensional electronic systems.

Students are encouraged early on to develop strong experimental skills for advanced laboratory work, including familiarity with numerical computation for data and image analysis and software packages for instrument automation. There exist many learning opportunities along these lines, from courses in microfabrication and laboratory work to independent research opportunities with various research groups. Undergraduate students are encouraged to explore and will find numerous opportunities for developing their research interests into junior or senior thesis projects leading to publication.

Physical Facilities

Research in applied physics covers a broad spectrum of activities distributed across campus. Instructional and research activities of the core faculty are housed in the Thomas J. Watson, Sr. Laboratories of Applied Physics, a 40,000-square-foot building with state-of-the-art research laboratories, a central microfabrication facility, faculty and student offices, and a conference room and instructional classroom, all nestled around a beautiful courtyard with a fountain pool.

Additional research laboratories and faculty and student offices are located in the Harry G. Steele Laboratory of Electrical Sciences, built in 1965 with funds from the Harry G. Steele Foundation and the National Science Foundation. The building, which is connected by an overhead bridge to the Watson Laboratories, conveniently also houses the Kavli Nanoscience Institute.

ASTROPHYSICS

Caltech is one of the world's preeminent centers of astronomical research. This is due to the combination of excellent human resources with premier observational facilities and computational infrastructure. Fundamental discoveries in astronomy and astrophysics are a part of Caltech's past, present, and future.

Students from either the astronomy or the physics options are best prepared to undertake research with faculty in the Cahill Center for Astronomy and Astrophysics. Students from related options such as planetary science, computer science, applied physics, and electrical engineering are also welcome.

Areas of Research

Astronomy and astrophysics are synonymous at Caltech. Caltech scientists and students are involved in many frontier areas of research, and have been known to open new ones. Research techniques include observations, theory, numerical simulation, advanced data analysis, laboratory astrophysics, and detector development. Projects and groups often bridge these areas of inquiry.

Topics of current research interest include: observational cosmology

and the nature of dark matter and dark energy; studies of the cosmic microwave background; galaxy formation and evolution; quasars and other active galactic nuclei and radio sources; studies of the dynamics and composition of galaxies and clusters; physics and evolution of the intergalactic medium; interstellar matter; local star and planet formation; extrasolar planetary systems; the structure of the galaxy; globular clusters; stellar abundances; supernovae, gamma-ray bursts, and other types of cosmic explosions and transient phenomena; neutron stars and black holes; accretion disks; digital sky surveys and astrophysics; numerical general relativity; gravitational wave astronomy and many others.

Research in planetary and solar system astronomy is often pursued in cooperation with groups in the Division of Geological and Planetary Sciences. New types of astronomical detectors and satellites, that can revolutionize various areas of astronomical research, are developed with groups in physics and colleagues at JPL.

In addition to maintaining a leading numerical general relativity group, Caltech theorists also use high-performance computing facilities for simulations of supernova explosions, merging black holes, cosmic structure formation, etc. Caltech is leading the development of novel tools for knowledge discovery in massive and complex astronomical data sets, many obtained with Caltech facilities.

History and Current Science at Observational Facilities

Observational astronomy is pursued both from the ground-based sites and from space-based platforms. Caltech operates, or has access to an unprecedented, comprehensive set of observational facilities, spanning the entire electromagnetic spectrum. Caltech is also playing a key role in opening a new window on the universe, the gravitational wave sky.

Historically, Caltech's pioneering role in astronomy started with Palomar Observatory (about 190 km from campus), funded by the Rockefeller Foundation. The first telescope on the mountain was an 18-inch Schmidt telescope built by Fritz Zwicky and used to conduct pioneering sky surveys for supernovae, potential planetary hazard asteroids, etc. The 200-inch Hale Telescope, constructed through the 1930s and 1940s, has been used to make many historical, fundamental discoveries ever since its commissioning in 1948, including the discovery of quasars, and many studies of stellar populations, galaxies, intergalactic medium, etc., and it continues to produce excellent science. Novel detectors and instruments were developed there, e.g., the first astronomical CCDs and infrared detectors as well as pioneering advances in adaptive optics in addition to optical and infrared spectroscopy. The 48-inch Samuel Oschin Telescope has made possible complete surveys of the northern sky, initially with photographic plates (including the historic POSS-I and POSS-II surveys), and now with large-format CCD array cameras. It is currently operating a uniquely wide field, high-cadence program, the Zwicky Transient Facility (ZTF). A much larger camera for this telescope, with a 47-square-degree field, started operation in 2018, as the Zwicky Transient Facility (ZTF). The 60-inch telescope has been roboticized, and is used to monitor sources discovered by sky surveys.

In the 1990s, funded mainly by the Keck Foundation, Caltech and

University of California constructed two 10-m telescopes on Mauna Kea, Hawaii. The W. M. Keck Observatory produced many recent discoveries in the fields of galaxy formation and evolution, intergalactic medium, extrasolar planets, cosmic gamma-ray bursts, etc. Caltech is a founding partner in the development of the Thirty-Meter Telescope (TMT), the first of the next generation of extremely large optical/infrared telescopes.

At meter to centimeter wavelengths, Caltech operates the Owens Valley Radio Observatory (OVRO) in a radio-quiet location about 400 km from Pasadena, near Big Pine, California. Its facilities include a 40-meter telescope, a growing 288 element long wavelength array which can image the entire sky every second, and a 6.1 meter telescope dedicated to observations of polarized radio emission from the galaxy. New radio and submm telescopes are in design and construction phases. From the 1980s until 2015, Caltech also operated the Caltech 10-m Submillimeter Observatory (CSO) on Mauna Kea in Hawaii, and a series of millimeter interferometers, culminating in the 23-antenna Combined Array for Research in Millimeter-wave Astronomy (CARMA) in the Inyo Mountains. These telescopes, currently being repurposed to new experiments, pioneered submm imaging and interferometry and mm wave interferometry, now carried out by the international Atacama Large Millimeter/submm Array (ALMA).

In Antarctica, Caltech's BICEP2 telescope, which measures the imprint of inflation's gravitational waves on the COSMIC microwave background, has been expanded and renamed the Keck Array.

On the space observations front, Caltech hosts NASA's Spitzer Science Center (SSC) and IPAC, which are principal national archives for astronomy. Caltech scientists lead or actively participate in a number of astrophysics missions, currently including the Spitzer Space Telescope, and the NuSTAR hard X-ray mission. Caltech and the Jet Propulsion Laboratory (JPL) are also leading the development of the forthcoming SPHEREx mission, that will study the early stages of the universe, galaxy formation, and formation of planetary systems. There are numerous close connections with JPL, that designs and operates a number of NASA's scientific missions. Finally, Caltech astronomers are major users of NASA's astronomical satellites, the Hubble Space Telescope, Chandra, Fermi, Herschel, Planck, etc., ALMA and the NSF's Jansky Very Large Array (JVLA).

Caltech is the headquarters for LIGO lab, which built and operates the world's most sensitive gravitational wave observatory, the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO), which in 2015 made the historic first detection of gravitational waves from a black hole binary. Several other black hole mergers have been detected since then, as well as the first gravitational wave detection of a merger of two neutron stars in 2017. Numerous other discoveries are expected as the operations continue.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

The Biochemistry and Molecular Biophysics (BMB) option has been established as an interdisciplinary program, at the interface of biology, chemistry, and physics, that seeks to understand the chemistry of life. Thus, BMB students 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.

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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, protein folding, biogenesis and quality control, electron transport proteins and bioenergetics, biological catalysis, macromolecular structure, membrane proteins, and biotechnology and biomolecular engineering. More specific examples of biological phenomena currently under study include the transduction of signals received by cell surface receptors into an appropriate response, as in chemotaxis or transmission of signals across synapses in the nervous system; the replication of DNA; the biochemical networks that control initiation and termination of cell division; the controlled transcription of DNA sequences in the genome into RNA and the processing of this RNA into mRNA and the subsequent translation into protein; energetic principles and molecular mechanisms that underlie the biogenesis of nascent proteins and maintenance of protein homeostasis in the cell; the molecular mechanisms controlling the differentiation of precursor cells into specialized cells such as neurons, lymphocytes, and muscle cells; the mechanisms by which synaptic transmission in the brain is regulated during thinking and the formation of memories; the processes, driven by fundamental principles of chemical bonding and molecular energetics, by which a given linear sequence of amino acids folds into a specific three-dimensional structure in the appropriate cellular environment; how electrons move within a cell to accomplish the many redox reactions necessary for life; how light is harvested by photo-pigments and is perceived in vision; the function of integral membrane proteins in energy and signal transduction processes; and the mechanisms by which enzymes both efficiently and specifically catalyze biochemical interconversions. This fundamental understanding of the molecular basis of biological processes provides a powerful base for the development of applications in medicine, including biotechnology and rational drug design, and in the chemical industry, where nucleic acids, proteins, and their analogs are now being used in the development of chemical systems for novel applications, and where mutagenesis and selection systems are used to produce novel materials.

BIOENGINEERING

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

Areas of Research

- **Bioimaging** (Cai, Dickinson, Gharib, Lester, Meyerowitz, Pierce, Shapiro, Yang)
Biophotonics, advanced imaging technologies, computational image analysis, noninvasive biomedical imaging, single-molecule technologies, flow-field imaging technologies, in situ amplification.
- **Bioinspired Design** (Gharib, Greer, Hajimiri, Ismagilov, Murray, Shapiro, Tirrell, Winfree)
Engineering physiological machines, engineering self-powered technologies, control systems, synthetic heteropolymers, and self-healing circuits and systems.
- **Biomechanics** (Bhattacharya, Dickinson, Gharib, Greer, Meyerowitz, Phillips, Roukes)
Molecular and cellular biophysics, cardiovascular mechanics, muscle and membrane mechanics, physiology and mechanics of flapping flight, multicellular morphodynamics, cell-biomaterial interactions.
- **Biomedical Devices** (Burdick, Emami, Gharib, Hajimiri, Heath, Ismagilov, Meister, Roukes, Shapiro, Siapas, Tai, Yang)
BioNEMS, BioMEMS, laboratories-on-a-chip including microfluidic systems, neural networks, microscopes and diagnostics, novel measurement principles, neural interfaces and prostheses, locomotion rehabilitation, molecular imaging during surgery.
- **Cell and Tissue Engineering** (Arnold, Elowitz, Gharib, Gradinaru, Ismagilov, Shapiro, Tirrell)
Multicellular morphodynamics, principles of feedback between tissue mechanics and genetic expression, non-natural protein biomaterials, cell-biomaterial interactions, developmental patterning.
- **Molecular Medicine** (Baltimore, Bjorkman, Davis, Deshaies, Gradinaru, Hay, Ismagilov, Lester, Mazmanian, Pierce)
Engineering immunity, cancer vaccines, AIDS vaccine, novel anti-cancer therapeutics, Parkinson's disease, schizophrenia, Huntington's disease, nicotine addiction, microbiome perturbations in disease, molecular basis of autism, programmable chemotherapies, conditional chemotherapies, nanoparticle drug delivery.
- **Molecular Programming** (Aravin, Murray, Pierce, Qian, Rothmund, Winfree)
Abstractions, languages, algorithms, and compilers for programming nucleic acid function, molecular information processing, molecular complexity theory, free-energy landscapes, metastable

ble systems, self-assembly across length scales, algorithmic self-assembly, synthetic molecular motors, in vitro and in vivo nucleic acid circuits.

- **Synthetic Biology** (Aravin, Arnold, Elowitz, Gradinaru, Ismagilov, Murray, Pierce, Qian, Rothemund, Shapiro, Tirrell, Winfree)
Principles of biological circuit design, genetic circuits, protein engineering, noncanonical amino acids, nucleic acid engineering, rational design, directed evolution, metabolic engineering, biofuels, biocatalysts, elucidation of systems biology principles using synthetic systems.
- **Systems Biology** (Aravin, Cai, Doyle, Elowitz, Goentoro, Heath, Ismagilov, Lester, Meister, Meyerowitz, Murray, Phillips, Sternberg, Winfree)
Roles of circuit architecture and stochasticity in cellular decision making, feedback, control, and complexity in biological networks, multicellular morphodynamics, principles of developmental circuitry including signal integration and coordination, spatial patterning and organ formation, principles of feedback between tissue mechanics and genetic expression, neural development, and disease.

BIOLOGY

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

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

Areas of Research

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

The programs in cellular, molecular, and developmental biology are based upon approaches derived from biochemistry, biophysics, and genetics that offer new possibilities for expanded insight into

long-standing problems. Neurobiology is a major area of emphasis within the Division of Biology and Biological Engineering. A comprehensive program of research and instruction in neurobiology has been formulated to span from molecular and cellular neurobiology to the study of animal and human behavior, including the computational modeling of neural processes.

A geobiology option is described in the geological and planetary sciences section.

Physical Facilities

The campus biological laboratories are housed in seven buildings: the William G. Kerckhoff Laboratories of the Biological Sciences, the Gordon A. Alles Laboratory for Molecular Biology, the Norman W. Church Laboratory for Chemical Biology, the Mabel and Arnold 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 high throughput sequencing and microarray analysis facility, and a protein expression and purification center.

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

CHEMICAL ENGINEERING

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

Areas of Research

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

- **Biological Design and Engineering.** Protein engineering by evolution and machine learning. New-to-nature biocatalysis for sustainable production of pharmaceuticals and specialty chemicals. Gene editing and genome engineering of plants.
- **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 melts, gels and solutions. Optical and rheological properties of polymers. 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. Plant synthetic biology, bioengineering, and biotechnology.
- **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.
- **Chemical Dynamics and Surfaces:** Kinetic-energy-driven, non-catalytic reactions with applications in plasma processing and astrophysical environments. Eley-Rideal reactions and collision-induced dissociation at surfaces. Water-splitting and carbon dioxide dissociation at oxides.
- **Complex networks of reactions, cell, and organisms in space and time.** Studies of microbial communities in environment and interactions of microbial communities with their human host.
- **Microfluidics.** Science of single molecules and cells. Fundamental studies of fluid flow and interfacial phenomena. Engineering of solutions to diagnostic and therapeutic problems in Global Health, including antibiotic resistance.
- **Nanotechnology.** Aerosol synthesis of nanoparticles for micro-electronic and photovoltaic applications. Electrospinning and electrospinning of nanostructured electrolytic materials for energy conversion and desalination. Novel electrodes for fuel cells, batteries, and super capacitors. Nano-membranes. Nanoparticles for biomolecule delivery to plants.
- **Environmental Chemical Engineering.** Physics and chemistry of atmospheric gases and aerosols, bioaerosols, climate change, biodegradation of persistent chemicals. Sustainable agriculture through rhizosphere engineering.
- **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. Data analysis and machine learning.
- **Physics of Complex Fluids and Soft Matter.** Structures, phase

transitions, and dynamics of polymers, liquid crystals, surfactant solutions, gels, colloidal dispersions and active matter.

- **Nanoscale Thermodynamics and Dynamics.** Flow and crystallization of materials in nanoscale confinement. Wall effects, lattice melting, capillary condensation. Structure, transport and charging/discharging in confined electrolytes.

Physical Facilities

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

CHEMISTRY

Caltech offers exciting opportunities for study and research at the frontiers of chemical science. With approximately 30 faculty, the chemistry program provides depth in the traditional areas of chemistry—organic and inorganic chemistry, chemical 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 post-doctoral research fellows. Crellin and Gates laboratories house several research groups, the divisional instrumentation facilities, and the divisional administrative offices. Synthetic research groups occupy the Arnold

and Mabel Beckman Laboratory of Chemical Synthesis and Church laboratories. The Braun Laboratories and the Broad Center for the Biological Sciences house biochemical groups and are shared with the Division of Biology and Biological Engineering. The Arthur Amos Noyes Laboratory of Chemical Physics is one of the major research facilities for chemical physics and inorganic chemistry and is adjoined by the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory. Chemistry groups recently joined several chemical engineering colleagues in the new Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering. A number of resource centers serving researchers of the division are located in the Beckman Institute.

CIVIL ENGINEERING

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

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

Areas of Research

Graduate work leading to advanced degrees lies chiefly in the following fields: structural engineering and structural dynamics; earthquake engineering; applied mechanics; geotechnical engineering; aerospace structures; and environmental engineering (see also environmental science and engineering). In the past few years, graduate students and members of the faculty have pursued a variety of research programs, including the analysis of structures subjected to earthquakes and other dynamic loadings; optimal performance-based structural design; system identification and control of structures; structural health monitoring; the use of finite element methods for structural analysis; seismic risk and structural reliability; earthquake early warning systems; mechanics of soil and other granular materials; and mechanics of space structures. Students whose interests are in environmental problems may enroll for graduate degrees in either civil engineering or environmental science and engineering.

Physical Facilities

Civil engineering activities are housed in two buildings: the Gates-Thomas Laboratory and the W. M. Keck Engineering Laboratories..

Excellent computing facilities are available through the campus computing network and in the specialized computing centers of various research groups. Seismic instrumentation networks include the Southern California Seismic Network and the Community Seismic Network.

COMPUTATION AND NEURAL SYSTEMS

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

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

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

Areas of Research

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

tional MRI, TMS, and tDCS; decision making, attention, awareness, emotion, and consciousness in the primate brain using a combination of neurophysiological, psychophysical, and computer modeling techniques; cognitive psychology; and the study of evolution in natural and artificial systems.

COMPUTER SCIENCE

Computing is a ubiquitous tool in all areas of study and research at Caltech. Computer science focuses on the theory and technology of computation itself: it is the study of information, and of the structures that communicate, store, and process information. Whether these structures are expressed in hardware and called machines, in software and called programs, or in nature or society, the fundamental concepts are similar.

Students of the computer science option within the Computing & Mathematical Sciences department at Caltech do not specialize along traditional lines that divide hardware and software, systems and applications, or theory and experiment. Rather, a unified approach to the design and analysis of computing structures is taken both in courses and in research. Managing the great complexity of useful systems requires a representation of computations amenable to both mathematical treatment and implementation. Whether the system is artificially designed (such as a multi-core processor), or naturally occurring (such as a molecule), the computer scientist formalizes the computation performed by the system and provides a systematic analysis of its requirements and formal guarantees on its outcomes.

Areas of Research

Research and advanced courses leading to the Ph.D. degree in computer science are concentrated in the following areas: quantum and molecular computation; parallel and distributed computation; theory of computation; information theory; machine learning and applications; computational economics; computer vision; computer graphics; discrete differential geometry; networking and power systems. Research projects frequently involve work in several of these areas, with both theoretical and experimental aspects, as well as connections with such fields as mathematics, physics, biology, economics, and electrical engineering. Crosscutting themes include:

- **Physical Implementation of Computations.** Computations must ultimately be implemented in some physical medium (e.g., semiconductor electronics, DNA self-assembly, quantum states of elementary particles, molecular electronics). Caltech has been a leader in the early development, engineering, and design of very large scale integrated (VLSI) circuits. Beyond VLSI, efforts are under way to understand quantum, biomolecular, and molecular electronic substrates as possible media for future computing machines. As was the case with semiconductor electronics, Caltech computing can draw on the world-class expertise of its biology, physics, and chemistry departments as it tackles

the many challenging opportunities that these new substrates present.

- **Robust Modeling of Physical Systems.** Caltech computer science has a unique focus in developing rigorous and robust models of the physical world. These models are mathematically and physically sound, often derived from differential geometric principles, and serve as a basis for computer graphics and vision research, as well as the simulation of mechanical, optical, and biological systems.
- **Systematic Design.** A key theme in the Caltech computer science option is the systematic design of systems at all levels. This theme shows up in the design of numerical algorithms for physical simulation and computer graphics, design of concurrent and distributed systems, abstractions for physical computing substrates, design of learning systems, design of programming languages, automated optimization of computations for both software and hardware implementation, as well as control and optimization of networks. The success of computer systems has allowed the building of systems of unprecedented scale and complexity. These systems can only be understood and managed if we carefully contain the complexity involved by systematically defining and exploring their design space.
- **Theory.** A strong theoretical understanding is the necessary foundation for systematic design, analysis, and verification. The theory of computation focuses on deep mathematical problems, many of which have substantial technological impact. Theory in computer science at Caltech includes traditional areas such as complexity algorithms, theories of numerical computation, optimization, probability, and game theory. But theory is not relegated to a single group, and has strong connections to all disciplines represented at Caltech.
- **Networks & Distributed Systems.** Modern networks and distributed systems are undoubtedly the most complex and critical pieces of infrastructure that the world has created. This includes communication networks as well as power networks, social networks, cloud computing, and more. The massive scale and exponential growth of such networks presents unique algorithmic, computational, and economic challenges. Research at Caltech approaches these challenges through a combination of rigorous design, systematic analysis, and interdisciplinary collaboration.
- **Machine Learning.** In our increasingly data-rich world, it is more important than ever to develop principled approaches that can intelligently convert raw data into actionable knowledge. At Caltech, we take a broad and integrated view of research in data-driven intelligent systems. The Decision, Optimization and Learning group brings together researchers from machine learning, optimization, applied math, statistics, control, robotics, distributed systems and human-computer interaction to form an intellectual core pertaining fundamental and applied research from statistical machine learning to

statistical decision theory through optimization.

- **Interdisciplinary Research.** Computer simulations, modeling, and analysis are key enablers, allowing all fields of science to advance rapidly. Furthermore, insights into computational management of information helps us understand information processing issues in natural systems (from cells and neurons to financial markets and social networks) and build hypothetical models that advance our understanding of natural cognition. These relations provide many opportunities for scholars in computer science to work closely with colleagues throughout Caltech. The Information Science and Technology (IST) initiative facilitates and promotes such interdisciplinary research (see ist.caltech.edu).

Physical Facilities

The computer science option has excellent computing facilities ranging from high-performance workstations to multiprocessors and supercomputers. The Computing & Mathematical Sciences department maintains a large computer lab open to students and offers a large collection of software for a wide range of applications. Students have easy access to state-of-the-art equipment. The Institute libraries maintain a large collection of journals in computer science and related fields.

COMPUTING AND MATHEMATICAL SCIENCES

Data-driven modeling is becoming increasingly critical in diverse application domains such as machine learning, vision, control systems, biological and engineered networks, neuroscience, economics, and privacy, as well as in many areas of the physical sciences, including high energy physics, earthquake modeling, astronomy, and exploration geophysics. There is enormous potential for research on data-intensive activity of this type, which is highlighted by the emergence of new fields such as “Big Data,” “Decision Science,” and “Network Science.” However, the theoretical foundations of these subjects remain underdeveloped, limiting our understanding and development.

The mission of the CMS graduate program is to address this need by exploring and developing the fundamental mathematical, computational, and economic tools necessary to advance data-intensive science and engineering. That is, we aim to forge the algorithmic foundations necessary to move from data, to information, to action. Key to this mission is a core focus on “algorithmic thinking.” Algorithms are not just the basis for advanced technology, they are intrinsic components of diverse fields such as biology, physics, and economics. Studying the structures and mechanisms that communicate, store, and process information from this viewpoint—whether these structures are expressed in hardware and called machines, in software and called programs, in abstract notation and called mathematics, or in nature and society and called biological or

social networks and markets—is crucial to pushing scientific boundaries. Simply put, it is almost impossible to do research in any scientific or engineering discipline without the ability to think algorithmically.

Because of the diversity of fields where algorithmic thinking is fundamental, there are broad differences in how algorithms are formalized, applied, and studied across areas. Over the years, these differences have been codified and the “language of algorithms” is actually quite distinct across, e.g., computer science, applied math, and electrical engineering. However, a broad view of algorithmic thinking is crucial to scientific breakthrough; and the goal of this program is to train scholars to have an interdisciplinary, cross-cutting view of algorithms.

Faculty and students in CMS are active in a broad array of research areas. Some of these include algorithms, complexity, algorithmic economics, feedback and control, inference and statistics, information systems, machine learning, networked systems, vision, optimization, quantum information, scientific computing, and uncertainty quantification.

CONTROL AND DYNAMICAL SYSTEMS

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

Faculty and students in CDS are active in a number of research areas. The primary theoretical areas of research include stochastic and nonlinear dynamical systems, multiscale modeling, optimal and decentralized control, system identification and estimation theory, Bayesian modeling and analysis, uncertainty quantification, and communications and information theory. Active applications include networking and communication systems, embedded systems and formal verification, robotics and autonomy, molecular and systems biology, integrative biology, human physiology, economic and financial systems, computing systems, physics of fluids, quantum mechanics, seismology and earthquake engineering, and space systems.

ELECTRICAL ENGINEERING

Electrical engineering at Caltech emphasizes both devices and systems. Closely allied with computation and neural systems, applied physics, bioengineering, computer science, and control and dynamical systems, it offers students the opportunity for study and research, both theoretical and experimental, in a wide variety of subjects, including wireless systems, photonics, quantum information science, modern

optics, biophotonics, MEMS/NEMS, solid-state materials and devices, power electronics, energy systems, control theory, data science, nanoscale systems, signal processing, learning, data compression, and communications.

Areas of Research and Physical Facilities

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

- *Bio-Electronics, Bio-Optics, and Medical Imaging*

(Azita Emami, Ali Hajimiri, Alireza Marandi, Axel Scherer, Yu-Chong Tai, Lihong Wang, Changhuei Yang)

Electrical engineering has broadly impacted biomedicine.

Integrated circuits are used to detect biological matters, such as DNA and proteins, in various (e.g., electrical, magnetic, optical) sensing modes with high sensitivity. Applications include microarrays and point-of-care. MEMS and nanotechnologies are developed for a new generation of micro-implants. Examples include retinal implants, drug delivery pumps, and bio-analyte sensors. Optical technologies are developed for medical imaging. Current areas of interest include optofluidics, wavefront shaping, wide field-of-view imaging, chip-scale microscopy, Fourier ptychographic microscopy, photoacoustic tomography, microwave-induced thermoacoustic tomography, and light-speed compressed ultrafast tomography.

- *Circuits and VLSI* (Azita Emami, Ali Hajimiri)

Analysis, design, simulation, verification, and testing of integrated circuits for various applications, such as high-speed and wireless communications, wireless local-area networks, highly stable frequency sources, distributed integrated circuit design techniques for ultrahigh speed silicon-based circuits, system and circuit design for multi-band systems, single-chip spectrum analyzers, performance limitation of A/D and D/A data converters, and robust circuit-design techniques. Projects also include millimeter-wave silicon-based circuits and arrays, flexible and lightweight arrays, wireless power transfer at distance, silicon-photonics and electronics integration, 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 chic.caltech.edu and mics.caltech.edu.

- *Control and Learning* (Venkat Chandrasekaran; John Doyle; Babak Hassibi; Victoria Kostina; Steven Low; Joel Burdick, Mechanical & Civil Engineering; Richard Murray, Control & Dynamical Systems)

Theoretical research is conducted in all aspects of control, with emphasis on robustness, multivariable and nonlinear systems,

optimal control, networked control with information constraints, learning for dynamical systems, online learning and control, control-theoretic perspectives on deep learning, and reinforcement learning. Theoretical developments are applied to a wide variety of areas, including internet, autonomous systems, wireless, power systems, cell biology, autonomy, neuroscience, medical physiology, turbulence, wildfire ecology, earthquakes, economics and finance, and foundations of physics.

- *Devices* (Ali Hajimiri, Alireza Marandi, Axel Scherer, Yu-Chong Tai, Lihong Wang, Changhui Yang, Amnon Yariv)

Research on devices in the Electrical Engineering department deals with a variety of fundamental topics including semiconductor physics, quantum mechanics, electromagnetics, and optics for developing hardware technologies for applications including sensing, communication, computing, and imaging. These devices can range in size from kilometer scale (such as antenna arrays for radio astronomy), to nano scale (such as building blocks of electronic and photonic integrated circuits).

- *Electromagnetics, RF, Microwave Circuits, and Antennas* (Azita Emami, Andrei Faraon, Ali Hajimiri, Mohammad Mirhosseini, Sander Weinreb)

Electromagnetics spans most aspects of electrical engineering (and everyday life) from RF, microwave, and mm-wave to infrared and visible optical systems that form the underlying platforms for many of modern marvels. Research involves theoretical study, design, and implementation of devices and systems, such as resonators, radiators, and arrays in microwave and mm-waves, as well as silicon photonics integrated circuits in conjunction with active high speed electronics and photonics integrated circuits. Some examples of such systems include optical phased arrays (OPA) transmitters and receivers, lightweight flexible deployable active phased arrays for communications and power transfer, multimodality quantum computing qubits, and radio astronomy receivers and arrays. This area includes strong theoretical investigations as well as extensive experimental work in realization of these systems in practice.

- *Energy and Sustainability* (John Doyle, Ali Hajimiri, Babak Hassibi, Steven Low, Guillaume Blanquart (Mechanical & Civil Engineering), Adam Wierman (Computing & Mathematical Sciences))

Energy research at Caltech encompasses control, optimization, and economics of energy systems, especially future smart grid. The goal is to develop a thorough understanding of the world's largest and most complex cyber-physical network as well as an intellectual basis for its transformation into a more sustainable, dynamic, and open system. Current research spans optimal power flow problems, convex relaxations, electric vehicle charging, wireless power transfer, space solar power, energy storage, power system dynamics and control, electricity markets, nonconvex pricing, market power, and cascading failure.

- *Information and Data Science* (Katie Bouman, Venkat Chandrasekaran, Babak Hassibi, Victoria Kostina)
The information and data sciences are concerned with the acquisition, storage, communication, processing, and analysis of data. These intellectual activities have a long history at Caltech both in electrical engineering as well as in allied areas such as applied mathematics. Current research centers around activity at the interface of statistical inference, inverse problems, and machine learning, and has significant synergies with ongoing efforts in information theory and signal processing.
- *Information Theory* (Yaser Abu-Mostafa, Jehoshua (Shuki) Bruck, Michelle Effros, Babak Hassibi, Victoria Kostina, P.P. Vaidyanathan)
Theoretical work in a wide range of problems involving transmission, storage and manipulation of information, with strong links to optimization, statistics, control, learning, and wireless communications. Current research foci include bitrate/energy efficiency of computing systems, coding for control, computing with stochastic circuits, error correcting codes for digital storage, coding for delay-sensitive systems, feedback communications, multi-user information theory, parameter estimation with unconventional sampling strategies, random access communications, and random asynchronous computations.
- *Learning, Pattern Recognition, and Neural Networks* (Yaser Abu-Mostafa, Katie Bouman, Jehoshua [Shuki] Bruck, Michelle Effros, Pietro Perona)
Theoretical and applied research in machine learning. Current theoretical research directions include estimating the information (data and hints) needed to learn a given task, characterizing the computational complexity of computing with neural networks, and modeling how biological networks of neurons create brain function. Current applied research directions include applications of ML in biology and medicine, in computational imaging, in e-commerce and profiling applications, and in computational finance. Examples of recent projects include a data-driven approach to predicting the spread of COVID-19 in every U.S. county (Abu-Mostafa), an ML approach to medical diagnostics using low-resolution ultrasound (Abu-Mostafa), a learning-based approach to jointly optimize sensor and algorithm designs in computational camera pipelines in order to automatically discover new imaging strategies (Bouman), and a Our latest project is a data-driven approach to predicting the spread of COVID-19 in every U.S. county.theoretical investigation of how networks of neurons form, store, and retrieve memories (Effros). Learning tools are also used for more efficient uncertainty quantification in ill-posed inverse problems, to improve our underlying model of a physical system, and to incorporate more sophisticated knowledge into inference methods.
- *MEMS and Micromachining* (Alireza Marandi, Mohammad Mirhosseini, Axel Scherer, Yu-Chong Tai)
We exercise MEMS, Micro- and nanotechnologies to build var-

ious sensor and actuator devices. Current research projects focus on bioMEMS and microimplant applications, including integrated biochips, microfluidic chips, neuron chips, blood-count chips, neuroprobes, retinal implants and spinal cord implants, wireless ECG, etc. Hands-on fabrication of these devices is specially emphasized for every student in the laboratory at Caltech.

- *Networks and Wireless Communication* (Michelle Effros; Babak Hassibi; Victoria Kostina; Adam Wierman, Computing & Mathematical Sciences)
Research in networks and wireless communication at Caltech spans the spectrum from characterizing theoretical limits of communication system performance to developing algorithms to approximate those limits in practice. Current areas of interest include models and performance analysis for wireless networks, code design and capacity characterization for communication environments characterized by unknown or time-varying channel characteristics, novel modulation schemes, random access communications, remote control over wireless channels, and cloud and edge computing and resource allocation for energy-efficient computing.
- *Optimization* (Venkat Chandrasekaran, John Doyle, Andrei Faraon, Babak Hassibi, Steven Low)
Optimization is the science of choosing the best element from a collection subject to some constraints. Current research at Caltech spans the spectrum from theoretical foundations to algorithmic development and eventual deployment in applications. In the context of electrical engineering, optimization methods play a prominent role in signal processing, communications systems design, statistical modeling, control, and machine learning.
- *Quantum Information Science* (Andrei Faraon, Alireza Faraon, Marandi, Mohammad Mirhosseini)
Experimental and theoretical research on physical implementations of quantum information processing systems. Current areas of research include: quantum computing hardware (memory, logic, interconnects) based on integrated superconducting circuits, photonics, and acoustics components; architectures for scaling quantum networks and modular quantum computing based on quantum transducers; understanding the sources of quantum decoherence in solid-state qubits.
- *Signal Processing* (Katie Bouman, Venkat Chandrasekaran, Michelle Effros, Babak Hassibi, Pietro Perona, P.P. Vaidyanathan)
Theoretical and computer-oriented work on a wide variety of problems in digital signal processing, with strong links to optimization, statistics, inverse problems and other areas of applied mathematics. Research areas include sparse sensor arrays, sparse signal reconstruction, compressive sensing, phase retrieval, structured signal recovery, high dimensional statistics, array signal processing, multirate digital filters and filter banks, radar signal processing, genomic signal processing, spectrum

sensing, graph signal processing, asynchronous random access communication systems, and lossless source coding and channel coding. Other topics include novel machine learning algorithms with applications in computer vision, visual recognition and categorization, and computational imaging with systems that tightly integrate algorithm and sensor design to find hidden signals for scientific discovery and technological innovation.

- *Vision* (Katie Bouman; Michelle Effros; Pietro Perona; P.P. Vaidyanathan; Richard Andersen, Computation & Neural Systems; John Allman, Computation & Neural Systems) Theory and applications of computer vision. Psychophysics and modeling of the human visual system. Modeling of vision-based decision-making in humans and animals. Current emphasis is on visual object recognition; vision-based human-machine interfaces; perception and modeling of human and animal behavior. Areas of collaboration include statistical machine learning, artificial intelligence, neural networks, computer graphics, neurophysiology, psychology, applied probability, robotics, geometry, and signal processing.

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 materials science, chemistry, applied physics, chemical engineering, mechanical engineering, and environmental science and engineering. Areas of emphasis reflect this breadth of disciplines and include photovoltaics, photoelectrochemical cells, bio-fuels, fuel cells, batteries, thermoelectrics, hydrogen generation and storage, and nuclear energy.

ENVIRONMENTAL SCIENCE AND ENGINEERING

Research and teaching in the ESE program span the large scales of global climate variations, the local scales of urban air pollution, and the microscales of microbial ecosystems. Reflecting the interdisciplinary nature of the ESE program, it unites scientists and engineers

from Caltech's Division of Geological and Planetary Sciences, Division of Engineering and Applied Science, and Division of Chemistry and Chemical Engineering. Jointly they address, for example, how climate has varied in the past and how it may change in the future, how biogeochemical cycles and chemical reactions control the composition of the atmosphere and local air quality as well as the Earth's global energy balance, and how more efficient and effective ways of producing bio-fuels or remediating toxic waste can be found. The methods employed in research projects include laboratory studies of fundamental chemical and biological processes; field studies of microbial ecology and of atmospheric chemistry; and computational and theoretical studies of chemical and physical processes on molecular to global scales.

Students enter the ESE program with diverse backgrounds, from the basic sciences of physics, chemistry, and biology to applied science and engineering fields. The curriculum emphasizes interdisciplinary knowledge and is broad, yet it is flexible so that different backgrounds and focus areas can be accommodated.

Areas of Research

- **Atmospheric Chemistry and Air Pollution.** Atmospheric chemistry affects the composition of the atmosphere, properties of clouds, and local air quality. Research areas include cloud chemistry, aerosol chemistry and physics, trace gas photochemistry, and emission sources and transport and reaction pathways of organic species. The methods employed include laboratory studies of aerosol formation and of chemical reactions in the atmosphere; field campaigns with aircraft operated by ESE faculty; satellite missions carried out in collaboration with the Jet Propulsion Laboratory; and theoretical and modeling studies of tropospheric chemistry and the carbon cycle.
- **Environmental Chemistry and Technology.** Environmental chemistry and technology research in ESE addresses fundamental questions in heterogeneous atmospheric chemistry (e.g., chemistry of clouds, fogs, and haze aerosols), in aquatic chemistry, in oxidation and reduction chemistry and technology, in semiconductor photocatalysis, and in hydrogen production from sunlight via electrochemical water splitting.
- **Dynamics of Climate.** Climate dynamics research in ESE addresses fundamental questions about how Earth's climatic features are maintained, how they have varied in the past, and how they may change in the future. Research includes the large-scale dynamics of the atmosphere and oceans, the hydrologic cycle and how it responds to climate changes, monsoon dynamics, and the dynamics of the Southern Ocean, and climates of other planets. Methods employed include theoretical and modeling studies, analyses of observational data, and field campaigns to collect oceanographic data.
- **Biogeochemistry and Climates of the Past.** Biogeochemical research in ESE finds application at scales ranging from microbial ecosystems to the global carbon cycle. Current research interests include the marine carbon cycle and its geochemical record

in organic matter and carbonate minerals; microbial recycling of nutrients and carbon; and development and use of geochemical proxies for understanding the ancient environment, including its climate.

- ***Environmental Microbiology.*** Microorganisms are the primary drivers of global biogeochemical cycles and represent the most abundant and diverse forms of life on Earth. They catalyze critical biological transformation processes such as nitrogen fixation, oceanic primary productivity, and methane cycling. Microbial ecosystem research within ESE is focused on understanding microbial processes in terrestrial, marine, and extreme ecosystems. Research areas span a range of topics and field sites, including the study of lignocellulose degradation by termite gut microbiota, anaerobic cycling of carbon, nitrogen, and sulfur in microbial mats and sediments, and methane cycling in the ocean.

Physical Facilities

ESE laboratories and facilities are housed in the Linde + Robinson Laboratory for Global Environmental Science and in other nearby buildings of Caltech's Division of Geological and Planetary Sciences. The laboratories are equipped with a wide variety of state-of-the-art instruments.

- ***The Environmental Analysis Center (EAC)*** houses analytical instrumentation, for research that ranges from analyzing pollutants in groundwater to dating fossils. Its equipment includes instruments for electrochemistry, plasma emission mass spectrophotometry, gas chromatography, high-performance liquid chromatography, fluorescence spectroscopy, infrared spectrometry, gas chromatography–mass spectrometry, total organic carbon analysis, and electrophoresis and electrical particle size analysis. Scientists from across the Institute use the EAC for cutting-edge analytical studies.
- ***The Atmospheric Chemistry and Aerosol Laboratory*** is designed for studies of the photochemical reactions of gaseous and particulate pollutants. In two reaction chambers (28 m³ each)—the first of their kind when they were built—the chemical reactions that produce urban smog and atmospheric particles are investigated under precisely controllable conditions. They have revealed how the particles that make up smog form in the atmosphere. Research results obtained with them have been instrumental in designing effective air quality policies. They continue to be invaluable in studies of air pollution.
- ***The High-Precision Spectroscopy Laboratory*** is housed in a quiet room—a room with specially designed acoustic and electromagnetic insulation. Acoustic foam blocks sound waves and copper cladding around the entire room blocks electromagnetic waves. The noise-free environment allows us to achieve exquisite precision in laser measurements of radiative properties of greenhouse gases, aerosols, and atmospheric trace constituents: the properties of single molecules can be

measured. The measurements are the basis for climate models and for planning satellite missions to measure the composition of the atmosphere from space.

- ***In the Laboratory for Atmospheric Chemical Physics***, the interactions of light with molecules in the atmosphere are investigated to elucidate how pollution forms and to measure the atmospheric concentration of aerosols and greenhouse gases. Techniques are developed for the global monitoring of the atmosphere from mobile ground-based laboratories and from space-based instruments.
- ***In the Environmental Chemistry and Technology Laboratory***, collimated sunlight from the Linde + Robinson solar telescope is focused into photolysis reactors, where artificial photosynthesis processes are developed to convert water and carbon dioxide into energetic fuels. Additionally, the chemical nature of the air-water interface is studied, and new technologies are developed for storing electric energy in novel lithium-air batteries and for treating water, for example, by photovoltaically powered electrolysis or ultrasonically induced cavitation.
- ***The Geochemistry Clean Room*** is designed for trace metal analysis in an entirely metal-free environment. It has air cleansed of almost all particles, to be able to measure with high precision tiny traces of metals and radioactive isotopes found in ocean water and embedded in corals and in stalagmites. These measurements reveal information about how climate has varied in Earth's past and how carbon cycles between the biosphere, the atmosphere, and the oceans. The Clean Room is supported by a plasma mass spectrometry instrument room that contains two multi-collector instruments and a quadrupole instrument. The facility also contains a wet chemistry laboratory for the processing and analysis of environmental samples.
- ***The Biogeochemistry Laboratories*** provide capabilities for analyzing the structure, abundance, and isotopic composition of organic materials in environmental samples, ranging from organisms to sediments to rocks. Instrumentation includes gas chromatograph-mass spectrometers, isotope-ratio mass spectrometers with capabilities for bulk and compound-specific analysis, a spectroscopic water isotope analyzer, and a combustion elemental analyzer.
- ***In the Environmental Microbiology Laboratories***, the diversity and metabolic activities of microorganisms from terrestrial and marine ecosystems are characterized through cultivation, microscopic imaging, metagenomics, and molecular and isotopic analysis. Instrumentation includes anaerobic chambers, platforms for performing microfluidics-based analyses of the nucleic acid contents of environmental single cells, capillary sequencers, quantitative PCR, epifluorescence microscopes, and CAMECA secondary ion mass spectrometers (7f Geo and nanoSIMS 50L) available through the Center for Microanalysis.
- ***Fram High Performance Computing (HPC) Cluster***. Fram is

a (HPC) Cluster composed of 314 HP SL390 computer nodes with 12 cores available per node. The cluster is connected with a low latency, high bandwidth network called InfiniBand. In addition to the traditional computer nodes, it also has 60 GPU based nodes with a total of 180 Nvidia M2090 GPUs. This filesystem can perform at around 9.5 GB/s. Fram is the latest of many clusters used for analysis and simulation of climate dynamics.

Additionally, Caltech collaborates with the Naval Postgraduate School's Center for Interdisciplinary Remotely Piloted Aircraft Studies (Monterey, California). This center operates research aircraft for atmosphere science studies, including a Twin Otter aircraft that carries state-of-the-art instruments to measure atmospheric aerosol and cloud properties in situ. Faculty, students, and staff in the ESE program also have access to the supercomputer facility of the Division of Geological and Planetary Sciences, where they carry out simulations of dynamical processes in the atmosphere and oceans and of chemical reactions and transport processes affecting atmospheric chemistry.

GEOLOGICAL AND PLANETARY SCIENCES

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

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

The events that shaped Earth can be identified by studying the structure of rocks and their chemical and isotopic compositions. The absolute chronology of Earth and solar system history can be established by measurements of radioactive isotopes. These geological events have been intimately associated with the origin and evolution of life on Earth. The field of geobiology uses both geological

and genetic evidence to examine the impact of life on Earth and the impact of geological conditions on biology. The field of geochemistry includes studies of radiogenic and stable isotopes, petrology, chemical oceanography, and atmospheric chemistry. These tools are applied to the origins of igneous and metamorphic rocks, evidence of past climate change, tracing anthropogenic influences on Earth, and the structure of planetary interiors. The comparative study of the other planets—their atmospheres, surfaces, and internal structures—is important in our understanding of Earth and its place in the cosmos. The early history of the solar system can be approached by studies of extraterrestrial materials, including lunar samples, interplanetary dust grains, and meteorites.

Physical Facilities

The division is housed in four adjacent buildings, which are well equipped for modern instruction and laboratory work. They contain several seminar rooms and a library as well as student and faculty offices. Numerous computers are distributed throughout the division, including a facility for geographic information systems and remote sensing. Rock and mineral collections and sample preparation areas are available. There are modern laboratories equipped with a scanning electron microscope and electron microprobe; a variety of plasma-source, gas-source, thermal emission, and secondary ion mass spectrometers; optical-, infrared-, and Raman spectrometers; high-temperature furnaces and high-pressure apparatus including piston-cylinder, multi-anvil, diamond anvil, and shock-wave facilities. Cooperation with other departments on campus provides access to additional instrumentation for sample preparation and analysis.

Laboratories for molecular geobiology provide capabilities for culturing, manipulating, and studying a wide range of environmental microbes, including anaerobes. A sensitive magnetometer facility is designed for the study of both biomagnetism and paleomagnetism. 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.

HUMANITIES

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

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

Philosophy is concerned with the most fundamental issues involving the nature of the world and of human knowledge, values, and judgment. At Caltech, particular emphasis is placed on philosophy of the natural and social sciences, scientific inference, and philosophy of mind, psychology and neuroscience. In addition to survey courses we offer courses on more focused topics, including causality, probability, quantum mechanics, space-time, free will, consciousness, and on ethical questions raised by modern science and technology.

Visual culture at Caltech encompasses the study of art history, film, media, and scientific images. Students work to gain visual literacy, and to understand both the history of images humans may have been looking at for hundreds or even thousands of years, and the provenance, location, and nature of the images we see now in our every day lives. Some visual culture classes make use of the resources of the Huntington Library, Art Museum, and Botanical Gardens; the Los Angeles County Museum of Art; and other museums in the area.

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

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

Areas of Research

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

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

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

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

INFORMATION AND DATA SCIENCES

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

As such, the information and data sciences now draw not just upon traditional areas spanning computer science, applied mathematics, and

electrical engineering—signal processing, information and communication theory, control and decision theory, probability and statistics, algorithms—but also a range of new contemporary topics such as machine learning, network science, distributed systems, and neuroscience. The result is an area that is new, fundamentally different from related areas like computer science and statistics, and that is crucial to modern applications in the physical sciences, social sciences, and engineering.

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

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

INFORMATION SCIENCE AND TECHNOLOGY

Information science and technology (IST) is a multidivisional research area that includes participants from the biology, chemistry and chemical engineering, engineering and applied science, humanities and social sciences, and physics, mathematics and astronomy divisions. Areas of emphasis include networking and distributed systems, neuromorphic engineering and sensory-based machines, quantum computation and communications, molecular electronics and biochemical computing, biological circuit design, information flow in economic and social systems, and mathematical foundations of information.

Physical Facilities

IST is mainly centered around the Annenberg Center for Information Science and Technology and the Moore Laboratory. Research centers associated with IST include the Lee Center for Advanced Networking, the Center for Neuromorphic Systems Engineering, the Center for Biological Circuit Design, the Center for the Mathematics of Information, the Center for the Physics of Information, and the Social and Information Science Laboratory.

INTERDISCIPLINARY STUDIES PROGRAM

Interdisciplinary studies offer an educational alternative for undergraduates whose goals cannot be satisfied with a normal undergraduate option. The student gathers a two-person faculty committee, representing at least two divisions of the Institute, and chooses their own scho-

lastic requirements under this committee's supervision. Approval must also be obtained from the Curriculum Committee, a standing committee of the faculty. The interdisciplinary 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 310.)

MATERIALS SCIENCE

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

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Areas of Research

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

Physical Facilities

Research by the faculty, graduate students, and advanced undergraduates is conducted in the W. M. Keck Laboratory, the Harry G. Steele Laboratory, and frequently in the Kavli Nanoscience Institute (KNI) Laboratory, a core cleanroom facility dedicated to nanofabrication and characterization. The KNI Lab and its technical staff provide training and access to advanced instrumentation that support the nano- and microfabrication process from beginning to end. This includes resources for electron and ion beam lithography; optical lithography; thin-film and chemical vapor deposition; metal and oxide evaporation; dry etching; various processing techniques; metrology including a spectroscopic ellipsometer; a suite of microscopes, such as focused ion beams (FIB), scanning electron microscopes (SEM) with energy dispersive spectroscopy, and AFM. The KNI also manages a transmission electron microscopy (TEM) facility which houses a 300-keV scanning TEM instrument with high resolution and analytical capabilities.

Additional facilities for the characterization of materials include X-ray powder diffractometers with position-sensitive detectors. Material-preparation facilities include equipment for additive manufacturing, physical vapor deposition under ultra-high vacuum conditions, arc melting, induction melting, casting, rapid solidification, processing of ceramic powders, and high-energy ball milling. More specialized instruments include impedance spectrometers for transport and dielectric measurements, Mössbauer spectrometers, differential scanning calo-

rimeters and differential thermal analyzers, thermogravimetric analyzers, and gas adsorption analyzers.

In addition to the general-use equipment within materials science, a wide range of mechanical and microstructural characterization facilities are available elsewhere at Caltech including a scanning electron microscope with electron backscatter detectors, mechanical testing machines, nanoindenters, an in-situ mechanical deformation instrument, AFM, electrochemical instrumentation, and an electrical probe tester.

MATHEMATICS

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Areas of Research

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

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

Physical Facilities

The mathematics department is housed in the Ronald and Maxine Linde Hall of Mathematics and Physics and the W.K. Kellogg Radiation Laboratory. In addition to offices for the faculty and graduate students, there are classrooms, conference rooms, discussion areas, a lecture hall, and a lounge for informal gatherings of the students and staff. The mathematics collection is housed nearby in the Sherman Fairchild Library.

MECHANICAL ENGINEERING

Mechanical engineering at Caltech explores the boundaries between traditional disciplines of science and engineering in order to develop a fundamental understanding of interdisciplinary challenges and create advanced technology to address contemporary problems. Mechanical engineering encompasses three broad areas: (1) mechanics of materials, (2) systems and control, and (3) thermal sciences and fluid dynamics.

The educational program in mechanical engineering prepares students for research and professional practice in an era of rapidly advancing technology. It combines a strong background in the basic and engineering sciences with an emphasis on addressing the critical technological challenges of the day. It strives to develop professional independence, creativity, leadership, and the capacity for continuing professional and intellectual growth.

Areas of Research

- **Mechanics of Materials.** Studies in the field of mechanics of materials emphasize a fundamental understanding of mechanical behavior and failure of materials as well as its applications. Areas of interest include static and dynamic deformation and failure of homogeneous and heterogeneous solids, mechanical behavior of nanostructures, active materials, microstructure characterization and evolution, thin films, micro-electro-mechanical systems (MEMS), composites, fracture and frictional sliding of solids, earthquake source processes, seismo-mechanics, geomechanics, and granular media. Most problems emphasize bridging temporal and spatial scales and the development of advanced analytical, computational, or experimental techniques.
- **Systems and Control.** This area combines a broad range of mechanical engineering fields, including control systems, dynamics, kinematics, and mechanical design, as well as cross-disciplinary areas such as signal processing, computer control, engineering computation, electromechanical design, micro-electro-mechanical systems (MEMS) design, and bioengineering. General areas of interest include control theory, estimation theory, decision theory, and robotics.
- **Thermal Sciences and Fluid Dynamics.** This area encompasses experimental and computational research in fluid dynamics, heat and mass transfer, thermodynamics, and combustion. Specific research areas include Stokesian dynamics, granular materials, cavitation and multiphase flow, turbulent combustion, explosion dynamics, and flow-generated sound. Applications cover a range of scales from molecular to high Reynolds number flows. They include constitutive modeling of colloidal dispersions, micro/nanofluidic systems including Marangoni and thermocapillary forcing in thin liquid films, the formation of pollutants from combustion hydrocarbon fuels, instabilities of complex, reacting flows, and high-speed flows with shock waves. Inter-disciplinary activities in the group include research on geophysical phenomena, biomedical devices, bio-inspired propulsion, and application of control theory to fluid mechanics.

Physical Facilities

Students and faculty in mechanical engineering conduct research in laboratory facilities in a number of areas, including design and prototyping, flow visualization, heat transfer, robotics, bio/nano-mechanics, nano-mechanical testing, seismo-mechanics, biomolecular circuits, autonomous vehicles, explosion dynamics, T5 hypervelocity flow, and geomechanics. A number of High Performance Computing (HPC) clusters are available, including both CPU- and GPU-based architectures. Kavli Nanoscience Institute (KNI) is utilized for micro- and nano-fabrication, testing, and characterization.

MEDICAL ENGINEERING

The Andrew and Peggy Cherng Department of Medical Engineering at Caltech focuses on the applications of micro-/nanoscale engineering sciences and technologies to the design, analysis, and implementation of diagnostic, therapeutic, and monitoring devices for translational medicine.

Areas of Research

- **Affordable Medical Devices and Technologies** (Gao, Gharib, Hajimiri, Ismagilov, Pickar, Yang) Chairs for children with cerebral palsy, bed-sore mitigation, toxic material filters, saliva-based diabetes tests, handheld diagnostic devices, and remote medical tracking systems. Devices that provide freedom from disability.

Biomaterials (Gradinaru, Grubbs, Greer, Ismagilov, Shapiro, Tai) Biocompatible medical materials, nanoscale-engineered smart materials, device-tissue interface, and cell-material interactions.
- **Biomechanics & Bio-Inspired Design** (Burdick, Colonius, Gao, Gharib, Gradinaru, Shapiro) Bio-inspired self-propulsion technologies, control systems, optimization techniques, shape morphing, cardiovascular mechanics, biomolecular nanomechanics, and muscle and membrane mechanics.
- **Medical Diagnostic, Monitoring, and Therapeutic Implants** (Emami, Gao, Scherer, Tai) Microscale implants with new functionalities to interface intact tissues and/or to replace defective functions: retinal implants, spinal cord implants, ECG implants, cardiovascular implants, implantable pressure sensors, glucose sensors, drug delivery pumps, and implantable bio-analyte sensors.
- **Medical Diagnostic and Monitoring On-Chip Devices** (Emami, Hajimiri, Ismagilov, Scherer, Yang) Magnetic spectroscopy, bio-assay, and drug-screening platforms, micro-PCR and sequencer, and on-chip bio-sensors.
- **Medical Imaging and Sensing** (Colonius, Emami, Faraon, Gao, Gharib, Gradinaru, Greer, Hajimiri, Scherer, Shapiro, Wang, Yang) Medical photonics and sensors, advanced imaging technologies, micro flow-field imaging, computational image analysis, lensless microscopy-on-a-chip, diagnostic and therapeutic ultrasound, and shock waves, single-molecule detection and diagnostics,

magnetic spectroscopy, tera-hertz imaging, Raman spectroscopy, photoacoustic tomography, thermoacoustic tomography, optical time reversal (wavefront shaping/engineering), compressed ultrafast photography, holographic microscopy, non-invasive label-free biomedical imaging and magnetic resonance imaging, wearable biosensors.

- **Medical Nanoelectronics** (Emami, Gao, Hajimiri, Scherer) Integrated nanoelectronics and circuits for medical applications, extremely low power medical electronics and sensors, high bandwidth wireless communication devices, self-healing circuits and systems, on-chip tera-hertz sources, and systems-on-a-chip.
- **Micro/Nano Medical Technologies and Devices** (Burdick, Emami, Faraon, Gao, Gharib, Greer, Hajimiri, Ismagilov, Scherer, Shapiro, Tai, Wang, Yang) Biochips, bio-MEMS/NEMS, micro-/nano-fabrication, holographic microscopy, and photoacoustic microscopy for medical applications.
- **Nano & Micro Fluidics** (Gao, Gharib, Ismagilov) Micro-/nano-fluidics, drug delivery, and physiological machines.
- **Prosthetics** (Burdick, Emami, Tai) Neural prosthetics and direct brain-machine interfaces, human prosthetics for paralysis, pure-thought-based control of external electromechanical devices, computer-decoding algorithms for direct brain interface, and robotic fingers.
- **Wireless Medical Technologies** (Emami, Hajimiri, Gharib, Scherer, Shapiro, Tai) Wireless communications through skins and tissues for medical electronic implants, electrograms, wireless power transfer, and biotic/abiotic interfaces.

MICROBIOLOGY

Microbiology recognizes that microbial inventions have profoundly shaped every aspect of the biosphere and geosphere throughout Earth's history. Many important molecular and cellular processes in eukaryotes are now known to have first arisen in bacteria and archaea, and microbial metabolic activities control numerous geochemical cycles. Microorganisms have served and will continue to serve as model systems in many areas of science, ranging from basic biology and biochemistry, to the understanding of physical principles governing biological systems, to emerging questions of robustness, stability, and design in complex networks. Interactions among microbes within communities, as well as interactions between microbial communities and their environments, are poorly understood. Yet studying these interactions is key to understanding fundamental relationships in nature, such as: 1.) the feedback loops connecting microbial activities in aquatic or terrestrial habitats with changes in composition of the atmosphere, hydrosphere and geosphere, and 2.) the symbiotic associations that sustain diverse forms of life today. For example, the interactions between a mammalian host and its microbiota are essential to the host's normal functioning and development, not merely the cause of infectious disease. Due to their metabolic versatility, microorganisms are

likely to emerge as key engineering components for solving global societal problems, ranging from human health, to energy, to providing clean water to more than one billion people who currently live without it.

Caltech's version of microbiology is unique. Diverse faculty from four divisions (BBE, CCE, GPS, EAS) work together to train students in how to understand microbial systems at various spatial and temporal scales: from the molecular to the global, from the present to the past. This interdisciplinary training involves study of molecular and cellular biology, physiology, chemistry, ecology, and quantitative reasoning.

NEUROBIOLOGY

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Understanding the brain remains one of the great intellectual challenges for science. To grasp the function of this marvelous organ, one needs to investigate structures, mechanisms, and dynamics that span across many spatial and temporal scales. For example, when we hear a sound, our brain is sensitive to time delays of just a few microseconds, yet the memory of that sound can last a lifetime—11 orders of magnitude longer. The span is similar in the spatial domain. The sheer number of nerve cells in the brain, approximately 1,011, suggests a coarse-grained treatment that glosses over the details of the individual neurons, yet a single nerve cell and even a single molecule can play a decisive role. For example, activation of a single light receptor in our eye leads to a visual percept that can ultimately direct our behavior.

Neurobiology at Caltech does, indeed, span this range. Our laboratories work on the molecular structure and function of channels and receptors; the integration of such molecules into signaling organelles like the synapse; the structure and function of single neurons; the integration of neurons of diverse types into circuits; and the collective function of these circuits in controlling behavior, perception, memory, action, cognition, and emotion. Another area of emphasis concerns the developmental mechanisms by which these structures form: the differentiation of neurons in early life, the genetic mechanisms that guide their synaptic wiring plan, and how subsequent experience modifies these connections. There is also increasing interest in leveraging the basic neurobiological insights to an understanding of brain disorders. Finally, Caltech's traditional strength in engineering stimulates the development of new methods for brain science: from optical techniques to new twists of genetic engineering, to novel multi-electrode devices, to computational models and theories.

To further explore the range of brain research at Caltech—and enjoy some colorful pictures—please visit the neurobiology option website.

PHYSICS

Areas of Research

Students in physics will find opportunities for research in a number of areas where members of the faculty are currently active, including those listed below. Physics research at Caltech is often done in collaboration with scientists in the departments of applied physics, astrophysics,

planetary science, engineering, chemistry, biology, and other departments, as well as with collaborators at other universities and laboratories. Additional research programs and more detailed information can be found on the Caltech physics department website.

- **Experimental Elementary Particle Physics.** Activities in elementary particle physics are aimed primarily at discovering new particles and interactions physics beyond the Standard Model (BSM) complemented by precision measurements of SM processes. Experimental efforts employ hadronic colliders and electron, muon, and neutrino beams at several international facilities. Current experiments include:
 - ~ CMS searching for dark matter and other new particles and new symmetries up to the mass scale of several TeV at the Large Hadron Collider at CERN
 - ~ the NOvA and DUNE long baseline experiments at Fermilab, studying the pattern of masses, mixing and CP violation in the neutrino sector
 - ~ the Mu2e experiment, searching for physics beyond the standard model in charged lepton flavor violation
 - ~ a nascent effort to search for accelerator production of dark matter called LDMX
 - ~ the long-running SuperCDMS effort to directly detect scattering of galactic dark matter with normal matter.
- **Theoretical Elementary Particle Physics.** The particle theory group studies the unification of interactions based on string theory, the detailed properties of hadrons described by QCD, the quantum properties of black holes, the foundations of cosmology, including dark matter and dark energy, and other aspects of mathematical physics.
- **Condensed-Matter Physics.** Areas of interest include correlated electron systems, topological quantum systems, phase transitions, atomic and excitonic Bose condensation, nanomechanical and nanoelectronic systems, biosensors, quantum electromechanics, phonon physics, high-temperature superconductivity, graphene and carbon nanotube systems, quantum entanglement, dynamics of disordered systems, chaos, pattern formation, and systems far from equilibrium. Resources include numerous labs in the Caltech physics department, at the Kavli Nanoscience Institute at Caltech, and at the Jet Propulsion Laboratory.
- **Quantum Optics and Information.** Research on campus and at the Institute for Quantum Information at Caltech includes studies of the nature of quantum computation and quantum information, cavity quantum electrodynamics, algorithms and error correction techniques in quantum computation, and generally how quantum physics can be harnessed to improve the acquisition, transmission, and processing of information.
- **Experimental Atomic/Molecular/Optical Physics.** Experimental atomic, molecular, and optical (AMO) research at Caltech focuses on controlling and understanding complex quantum systems for a wide variety of scientific goals. Current experiments include

building arrays of ultracold atoms to study quantum information, metrology, many-body physics, and simulation of condensed matter systems; precision measurements in cold and ultracold polar molecules to search for fundamental symmetry violations; engineering atom-light interactions in photonic crystals; quantum physics of mechanical devices, hybrid superconducting quantum circuits, and optomechanical sensors; neurophotonics and neuromolecular sensing; development of quantum networks and communication and addressing fundamental questions in quantum information. Many of these research strands are collaborative efforts supported by the Institute for Quantum Information and Matter.

- **Nuclear Physics.** The interests of the nuclear group focus on performing precision measurements to search for new physics beyond the Standard Model. In particular, precision measurements of free neutron decay allow sensitive searches for new physics, while measurements of the neutron electric dipole moment may help explain the dominance of matter over anti-matter in the universe.
- **Astrophysics.** Research in this area covers a broad range of topics using observational tools covering the entire electromagnetic spectrum.
 - ~ The high-energy astrophysics group at the Space Radiation Laboratory (SRL) uses X-ray and gamma-ray detectors aboard spacecraft and balloons to investigate energetic processes from compact astrophysical objects, including gamma-ray bursts from neutron-star and black-hole systems, supernova and hypernova dynamics, and the development of stars and galaxies in the early universe.
 - ~ The cosmic ray group at SRL uses data from a variety of spacecraft to study the composition of energetic particles arriving from the sun, the local interstellar medium, and beyond, in order to understand the origin and acceleration of energetic particles in space.
 - ~ The millimeter/submillimeter astronomy group, with collaborators at the Jet Propulsion Laboratory, studies the solar system, star and planet formation, the interstellar medium, galaxies, galaxy clusters, and the epoch of reionization using data from the Caltech Submillimeter Observatory (CSO) and other facilities. Future-oriented programs include the development of new superconducting detector technologies and instruments for use at these wavelengths, also in collaboration with JPL, and an effort to move the currently idle CSO to a new, more sensitive site.
 - ~ The Galactic compact objects astrophysics group studies black holes, neutron stars, and white dwarf systems, including gravitational wave sources detectable by future space missions such as LISA. The group uses telescopes at Palomar, Kitt Peak and the Keck Observatory, as well as the radio telescopes of the NASA Deep Space Network.
- **Theoretical Astrophysics.** The TAPIR (Theoretical Astrophysics

Including Relativity) group carries out research on an ever-changing list of topics, including planets; stars, neutron stars, black holes and their interactions; gravitational-wave astrophysics; cosmology; the formation of stars and galaxies; and numerical and analytical general relativity.

- **Cosmology.** The observational cosmology group explores the structure and dynamics of the early universe using precise measurements of the cosmological microwave background radiation and large scale structures from detectors on the ground, on balloons, and on spacecraft. Efforts to directly detect dark matter are also under way. These experiments include an active program of detector development in collaboration with scientists at the Jet Propulsion Laboratory. Theoretical studies seek to understand the large-scale structure of the universe, including the physical nature of dark matter and dark energy.
- **Gravitational-wave Astronomy.** Observations from the LIGO and LISA projects seek to use gravitational radiation to study a variety of astrophysical sources. Theoretical studies are aimed at developing sensitive data analysis techniques and calculating gravitational-wave signals from sources such as coalescing black holes and neutron stars.

Physical Facilities

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

SCIENTIFIC AND ENGINEERING COMMUNICATION

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

SOCIAL AND DECISION NEUROSCIENCE

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

Areas of Research

This program is characterized by interdisciplinary research at the frontier of neuroscience, psychology, economics, and political science.

Examples of research topics of interest include the following:

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

Physical Facilities

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

SOCIAL SCIENCE

PHILOSOPHY AND GOALS OF THE SOCIAL SCIENCE UNDERGRADUATE CORE

The social science core curriculum initiates students in the study of how humans organize, decide, govern, and allocate their resources. It teaches students how to analyze and reason about individual behavior, markets, and other institutions. Our curriculum covers methods, as well as substance. The issues facing our students in the future will be different from those that are current, but the analytical principles and methodology needed to understand those problems will likely remain the same, albeit improved. Thus, the social science core curriculum

provides students with the knowledge and tools to, in the words of the catalog, “navigate the societal, political, and economic factors that influence, and are influenced by, their work.”

The objectives of the social science core curriculum can be broken into three broad categories of courses: introductory courses that teach basic principles; methods courses that seek to transmit skills and analytical tools; and courses exposing students to substantive ideas and problems in the social sciences. More concretely: “Fundamental ideas and principles” classes expose students to a broad and introductory overview of basic ideas in anthropology, economics, psychology, and political science. “Methodology and analysis” courses focus mainly on giving students the theoretical and empirical tools to analyze problems. They cover the theoretical modeling tools most commonly used in the social sciences, as well as statistical and econometric techniques that are needed to analyze data. “Substantive problems in social science: Individuals, institutions, and markets” courses expose students to an array of substantive questions in social science, from resource allocation via markets and prices, the workings of political institutions, the consequences of poor governance, the psychological basis of human behavior, and an understanding of financial markets.

SOCIAL SCIENCE GRADUATE PROGRAM

The Caltech Ph.D. program in Social Science is highly interdisciplinary, integrating economics, political science, quantitative history, econometrics, and finance. It makes extensive use of mathematical modeling, laboratory experiments, and econometric techniques. Research in the social sciences program at Caltech strongly emphasizes the understanding and analysis of the relationships between individual incentives, collective behavior, political and economic institutions, and public policy.

Areas of Research

- *Experimental Economics and Experimental Political Science.* Caltech social scientists were among the early pioneers in the field of laboratory experimentation and Caltech has maintained a strong leadership position and research presence in the field ever since. Examples of the kinds of laboratory studies the faculty are engaged in include the behavior and design of auctions and market-like mechanisms, public goods provision and related topics in public economics, the economics of networks and matching, decision theory, inter-personal bargaining, behavioral economics, committee decision making, and electoral competition. Many of our faculty engage in laboratory experimentation as part of their research agendas in economics and political science (Agranov, Camerer, Echenique, Nielsen, Palfrey, Plott, Saito, Shum, Sprenger). Considerable laboratory experimentation also focuses upon the workings of financial markets, and seeks to elucidate basic principles that underlie the pricing of assets,

trading, and information aggregation in these markets. Many of these experiments are conducted through the use of networked computers (see Facilities) in the William D. Hacker Social Science Experimental Laboratory (SSEL) and the Laboratory for Experimental Economics and Political Science (LEEPS). The real world provides another setting for experimental research outside the laboratory, and Caltech social scientists have conducted field experiments involving a wide variety of topics, ranging from decision making in organizations, social networks, and the behavior of different cultural groups ranging from college students, to urban Americans to African villagers.

- Economic Theory and Game Theory.*** Caltech has a strong research group in economic theory, which, together with rigorous training in statistics and econometrics forms the backbone of the core curriculum for the PhD program. Theoretical research at Caltech has played a key role in the design and practical implementation of new institutions that more efficiently allocate scarce resources and provide public goods. Some of this work has had important public policy applications. Prominent examples include the design of FCC auctions to allocate the electromagnetic spectrum for telecommunication, and the market for allocating and trading permits for pollution emissions in the Los Angeles basin. Much of this theoretical design research is complemented by experimental studies that provide a testbed for competing designs. There is an active group of faculty and graduate students working in the areas of the optimal design of contracts and markets (Cvitanic, Echenique, Plott), the economics of information (Pomatto, Tamuz), decision theory (Echenique, Pomatto, Rangel, Saito), game theory (Echenique, Palfrey, Pomatto, Saito, Tamuz) and matching Social Science and Research (Echenique). There are several active programs for inter-action between our theory faculty in the social sciences and the faculties of computer science and applied mathematics. This is formally organized around two interdisciplinary centers, the Lee Center for Advanced Networking and the Social and Information Science Laboratory (SISL), with the latter offering a bi-weekly seminar coordinated between the computer science department and the social sciences faculty and featuring speakers in eco-nomics, computer science, game theory and related disciplines. There are many informal connections that reinforce the formal connections, including research collaborations between faculty and graduate students in these different areas.
- Political Economy and Political Science.*** Caltech has a long tradition of strength in research that spans the boundary of the economics and political science disciplines. Research in political economy at Caltech continues to be a major strength of the program and provides a natural bridge that unites the faculty in economics, political science, and quantitative history. The focus of research in political economy and political science at Caltech

emphasizes rigorous theoretical modeling drawing heavily upon techniques from economic theory and game theory, combined with empirical studies using highly sophisticated quantitative analyses of a wide variety of data sources: experimental, survey, field, voting, and historical data. Ongoing political economy research areas of the current faculty include: the interacting forces of bargaining, voting, and communication in commit-tees, legislatures, bureaucracies, and assemblies (Agranov, Gibilisco, Hirsch, Katz, Lopez-Moctezuma, Palfrey, Plott); the Voting Technology Project, a joint Caltech-MIT research venture, established in 2000 to evaluate and improve the performance and reliability of U.S. balloting technology, registration systems, election administration, redistricting, and election law (Alvarez, Katz); political forces affecting judicial behavior (Hirsch, Shum), strategic voting in multicandidate and multi-stage elections (Alvarez, Kiewiet, Palfrey, Plott), the politics of inequality and redistribution (Agranov, Palfrey) and several areas of comparative and international politics, including studies of the causes and consequences of corruption, domestic unrest, and international conflict (Ensminger, Gibilisco, Lopez-Moctezuma).

- **Financial Economics.** Caltech has built a small but very active research group in finance. The researchers in this group are working on a range of topics in mathematical finance (Cvitanic), empirical studies of venture capital and entrepreneurship (Ewens), asset pricing (Cvitanic, Jin, Plott, Roll), dynamic contracting (Cvitanic), and behavioral finance (Camerer, Jin, Plott). There is a regular seminar series in finance that features distinguished researchers from around the world. Caltech faculty outside the finance group itself are also engaged in empirical research in financial economics. These include experimental Areas of Study and Research studies of asset markets (Camerer, Palfrey, Plott), interest rate policy making by the Federal Open Market Committee (Lopez-Moctezuma), and online credit markets (Xin).
- **Behavioral Economics.** Research in behavioral economics at Caltech overlaps all of the above groups. Laboratory experimental research discovers interesting behavioral anomalies and can also test theoretical models designed to account for such anomalies. On the theoretical side, much of the game-theoretic and decision-theoretic research at Caltech is motivated by experimental observations, leading to extensions or modifications of standard models. These extensions in turn suggest experimental designs that are then implemented in the laboratory by our faculty and graduate students. Faculty research in political behavior (Alvarez, Katz, Kiewiet) and behavioral finance (Camerer, Jin, Plott) are complementary and add strength more generally to understanding social behavior. We also have on our faculty a small but very active group conducting research at the boundary of biology, psychology, and the social sciences (Adolphs, Camerer, Mobbs,

O'Doherty, Rangel). This group offers a separate PhD option focused on the behavioral neuroscience of decision making (see the catalog entry for "Social and Decision Neuroscience"). Utilizing fMRI brain-imaging, eye-tracking, and other biological measurement technologies, this group, often in collaboration with other social science faculty and graduate students, has begun to explore the neural foundations of decision making in individual choice, game theoretic, and market settings.

- **Quantitative History.** Just as with the theoretical, experimental, and empirical work using contemporary, historical research conducted at Caltech employs mathematical modeling and sophisticated statistical techniques to attack a wide range of historical questions. Historical research conducted at Caltech addresses questions that cut across economics, political science, political economy, and even finance, often combining archival work with state-of-the-art statistical techniques. These include the development of capital and credit markets in Europe (Hoffman, Rosenthal), the evolution of wealth distribution from 1800 to the present (Rosenthal), the causes of recurrent financial crises in capitalist economies (Hoffman, Rosenthal), and the determinants of economic and technological growth.
- **Applied microeconomics and econometrics.** Empirical research in social science blends creative collection and analysis of field data with rigorous application of tools and methods from econometrics and statistics. We offer courses and supervise students in these areas. A number of faculty members specialize in empirical work in a number of fields, including finance (Ewens, Jin, Xin), industrial organization (Shum, Xin), political economy (Alvarez, Gibilisco, Katz, Kiewiet, Lopez-Moctezuma, Sherman, Shum), and behavioral economics (Camerer, Jin). Methodological areas of specialization include econometrics (Sherman, Shum, Xin), causal inference (Alvarez, Katz, Sherman, Shum), machine learning (Alvarez, Katz, Xin), and Bayesian statistics (Katz).

Physical Facilities

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

SYSTEMS BIOLOGY

Systems Biology seeks to understand how the parts of biological systems are integrated to produce the amazing machines, cells, organisms and ecosystems that exist in our world. We seek to define general principles of biological systems. Part of the effort involves defining the relevant parts and measuring how they change in a quantitative and comprehensive fashion as they carry out their functions. This task is the domain of genomics, proteomics, metabolomics, functional genomics, bioinformatics and other aspects of Network Biology and Bioinformatics. Another related task is to understand the “mechanisms,” the precise structures and interactions of those parts that ultimately produce biological function. This task requires Computational Modeling of potential mechanisms, coupled with Quantitative tests of the predictions of models by cell biological, molecular biological, and biophysical techniques. One particularly stunning feature of organisms is their ability to develop from a single fertilized egg; thus, Systems Developmental Biology is an important third theme of our program. This theme involves the study of how organisms generate complexity of cell types in a defined spatial organization by a sequential, contingent, irreversible cascade of molecular, cellular, and genomic processes.

Our goal is to train students who can seamlessly integrate diverse quantitative and experimental methodology and can balance the tension between global understanding and mechanistic insight. This training involves study of biology, mathematics, quantitative reasoning, computational and data analysis tools, and the rich experimental methods of the biological sciences.